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Versatile Applications, Challenges, and Future Prospects of Cottonseed Oil

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Abstract
Cotton crop basically serves the fiber need of mankind but it goes beyond the fiber and also add up to ensure food safety for growing populations. A Cottonseed contains 15-20% oils and is no longer considered a byproduct and is used for edible purpose. Cottonseed oil is an essential agricultural product derived from cotton processing, serving the food products market, pharmaceuticals, cosmetics, and the biofuels industry. Mechanical pressing and solvent extraction methods yield cottonseed oil containing both saturated and unsaturated fatty acids, with linoleic acid comprising 50-60% of its content. The combination of high oxidative stability together with tocopherol content ensures that cottonseed oil works well for food preparation during frying and baking activities. However, the safety of cottonseed oil consumption depends on refining methods since research shows gossypol toxicity and pesticide residues combined with an unbalanced omega-6 to omega-3 ratio. Cottonseed oil holds dual industrial significance, as its emollient and antioxidant properties make it valuable for both biodiesel production and cosmetic formulations. The cotton farming sector pursues organic cultivation and genetic modification as methods to boost oil production while minimizing the environmental effects. Now, research is focused on exploring modern extraction strategies built around enzyme-assisted and supercritical CO_2 methods which both boost the process's efficiency while reducing chemical solvent requirements. The rising market demand for plant-based oils alongside sustainable farming methods creates substantial opportunities to secure global food supplies while fostering renewable energy development and nutraceutical innovation. The paper examines cottonseed oil's structural composition, extraction methods, health impacts, industrial applications, and its sustainable prospects.

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Pamuk tohumu yağının çok yönlü kullanım alanları, zorlukları ve gelecekteki beklentileri

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Özet
Pamuk mahsulü temel olarak insanlığın lif ihtiyacını karşılar, ancak lifin ötesine geçerek artan nüfus için gıda güvenliğini sağlamaya da katkıda bulunur. Pamuk tohumu %15-20 oranında yağ içerir ve artık bir yan ürün olarak görülmemekte, gıda amaçlı kullanılmaktadır. Pamuk tohumu yağı, pamuk işleme sürecinden elde edilen önemli bir tarım ürünüdür ve gıda ürünleri pazarı, ilaç, kozmetik ve biyoyakıt endüstrisine hizmet eder. Mekanik presleme ve çözücü ekstraksiyon yöntemleri, içeriğinin %50-60'ını linoleik asit oluşturan, hem doymuş hem de doymamış yağ asitleri içeren pamuk tohumu yağı verir. Yüksek oksidatif stabilite ile tokoferol içeriğinin birleşimi, pamuk tohumu yağının kızartma ve fırınlama faaliyetleri sırasında gıda hazırlama için iyi sonuçlar vermesini sağlar. Ancak, pamuk tohumu yağı tüketiminin güvenliği, araştırmaların gossypol toksisitesi ve pestisit kalıntılarının dengesiz omega-6 ve omega-3 oranıyla birleştiğini göstermesi nedeniyle rafine etme yöntemlerine bağlıdır. Pamuk tohumu yağı, yumuşatıcı ve antioksidan özellikleri sayesinde hem biyodizel üretimi hem de kozmetik formülasyonları için değerli olması nedeniyle endüstriyel açıdan çift öneme sahiptir. Pamuk yetiştiriciliği sektörü, çevre üzerindeki etkileri en aza indirirken yağ

üretimini artırmak için organik yetiştirme ve genetik modifikasyon yöntemlerini uygulamaktadır. Şu anda araştırmalar, hem sürecin verimliliğini artıran hem de kimyasal çözücü gereksinimlerini azaltan enzim destekli ve süperkritik CO_2 yöntemleri etrafında geliştirilen modern ekstraksiyon stratejilerini keşfetmeye odaklanmaktadır. Bitki bazlı yağlara yönelik artan pazar talebi ve sürdürülebilir tarım yöntemleri, yenilenebilir enerji geliştirme ve nutrasötik inovasyonu teşvik ederken, küresel gıda tedarikini güvence altına almak için önemli fırsatlar yaratmaktadır. Bu makale, pamuk tohumu yağının yapısal bileşimi, ekstraksiyon yöntemleri, sağlık üzerindeki etkileri, endüstriyel uygulamaları ve sürdürülebilirlik beklentilerini incelemektedir.

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Introduction

The textile industry relies on lint production from cotton plants, which generates economic value. China, India, the United States, Pakistan, and Brazil are the leading cotton-producing countries worldwide. Significant work is been done to improve cotton seed yield via different conventional and advance breeding methods [1] the focus on byproducts of cotton crop is very little till now. Cotton is among the significant crops because its lint fulfills the requirement of textile industries and its seed is used for extracting edible oil. The byproducts of cotton are used for domestic and industrial purposes (Figure 1). Cottonseed oil is a valuable byproduct obtained after separating natural fibers from cotton seeds and then extracting oil from them. Seed contents makes about 50-60% of the total seed cotton yield and thus can contribute a considerable amount of oil [1]. Industrial companies extract cottonseed oil during the production of cottonseed meal and oil-based ingredients. Despite the common perception that cottonseed oil is a secondary product, it is widely used in animal and human food, cosmetics and paints. Germplasm screening is one of the powerful technique to determine the potential of genotypes for potential improvement areas of crop breeding [3]. The germplasm of cotton has been screened for cotton seed oil many times and it reveals that it ranges between 16-20% while protein contents ranges from 20% to 25%. While the mineral contents of seed do not impact their protein levels [4].

Hybridization is been used for centuries to improve cotton traits like seed cotton yield and fiber quality. It is now also been utilized for developing resistance against various pathogens and tolerance for many abiotic stresses [5]. Thus hybridization after screening can be a potential approach to improve inherent oil quantities in the cotton seeds. Extraction methods for cottonseed oil are crucial because they deliver advantages to nutritional areas and industrial facilities. Eating raw cottonseed as a single portion is risky because gossypol is toxic polyphenolic compound that makes it poisonous [6. 7].

Production and export of cottonseed oil occurs in huge volumes in the United States as well as India. The Chinese market uses cottonseed oil at its peak for edible purposes. Cottonseed oil replaces traditional soybean, palm and canola oil due to its neutral taste profile combined with high cooking tolerance [8]. The production chain of cottonseed oil fulfills its basic needs both for agricultural and food industry exports to international markets. The market demand of cotton seed oil keeps on increasing because of its functions both as edible purpose and industrial raw material. Cotton researchers have dedicated their efforts to resolve three main problems involving gossypol toxicities and pesticide residues while handling sustainable productions. Cottonseed oil continues to expand its market value as a useful agricultural commodity due to growing demand for vegetable oils and environmentally friendly farming practices which point toward considerable potential in food sector applications and pharmaceutical research and biofuel production. This review explores cottonseed oil structural features alongside extraction techniques, medical applications, safety considerations and industrial utilization possibilities.

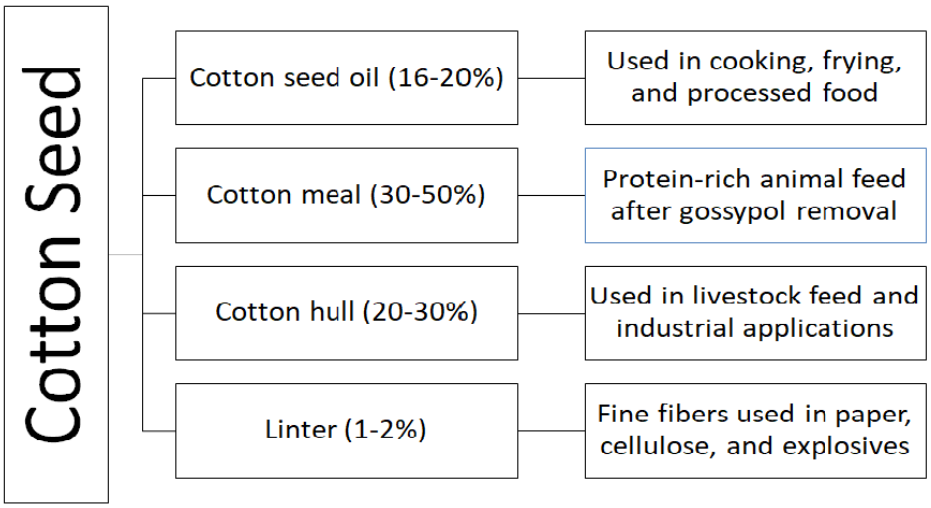

Figure 1 Percentages of byproducts of cotton and their usages

Cotton seed oil processing

The cottonseed oil industrial processing began in the nineteenth century when cotton mills started extraction of oil from seed during their manufacturing operations [9]. The scientific community initially discarded the substance until they found that it offered valuable commercial potential in food manufacturing. The process of oil extraction starts with cleaning operations followed by de-hulling after which oil extraction takes place and then refinement completes the procedure. The majority of oil extraction uses press methods along with solvent techniques and then requires degumming combined with neutralization, bleaching and deodorizing [6]. The oil processing methods accomplish double purposes to convert oil into edible food while ensuring extended storage period. Cottonseed oil serves as highly stable frying oil that people extensively use in food baking and frying and manufacturing operations. It has mild nutty flavor and preserve food during deep frying since it remains fresh for 12 months and has a 232°C smoke point [10]. Rich in tocopherols (vitamin E) along with sterols and antioxidants offer both nutritional qualities and stability to the substance [11].

Beyond food applications, cottonseed oil is used in pharmaceuticals and cosmetics as a natural moisturizer in lotions, hair products, and soaps [12]. The biological fuel market makes primary usage of cotton seed oil while industries utilize it to produce lubricants and paints. The substance qualifies as sustainable because cottonseed oil emerges as a processing byproduct so no production material becomes unnecessary waste [13, 14]. However, cotton farming poses three major challenges affecting oil quality: pesticide use, high water consumption, and the presence of gossypol, a naturally occurring toxin that makes unrefined cottonseed oil unsafe for direct consumption [15, 7]. Adopting organic and non-GMO cotton production can enhance ecological sustainability [16].

Chemical Composition of Cottonseed Oil

Cottonseed oil contains a balanced combination of saturated, monounsaturated, and polyunsaturated fatty acids, contributing to its stability during frying. Its primary fatty acid is linoleic acid (an omega-6 fatty acid), which makes a major part of cotton seed oil. While oleic acid (omega-9), palmitic acid, and stearic acid also found in comparatively less amounts [9]. Furthermore, tocopherols (vitamin E), phytosterols, and polyphenols help prevent spoilage and extend shelf life benefits [18]. Due to these properties, cottonseed oil is gaining popularity in food industries for margarine, salad dressings, and baked goods.

Regular consumption of cottonseed oil provides essential fatty acids that support heart health, as it is cholesterol-free and rich in linoleic acid [19]. This omega-6 polyunsaturated fatty acid plays a vital role in cell structure, skin health, and immune function [20]. However, excessive omega-6 intake relative to

omega-3 may promote inflammation and chronic health conditions [21]. Although the omega6: Omega3 is very high (15:1) in human diets, a relatively small ratios (3:1 or 4:1) are required to prevent pathogenesis of many diseases including hypertension, cancer, arthritis, diabetes, neurodegenerative diseases and coronary heart disease. However, a target of 2:1 to 1:1 of omega 6 to omega 3 is desirable in diet for optimal neurodevelopment and gene expression [22]. Pesticide residues are another problem of cotton seed oil. As much as 38% of cotton seed oil has some residues of pesticides including propenofos, chlorpyrifos, acephate and highest probability of monocrotophos. These chemical residues in edible oil is a big threat to human health but Bt. Gene has made this problem less effective as pesticide sprays has been reduced in Bt. cotton [23]. Additionally, gossypol is a natural polyphenol in unrefined cottonseed oil, which must be removed during processing to ensure safety for human consumption [24, 7]. World health organization has permitted 0.6 µg/mg free gossypol in edible oil, which can be ensured in cotton seed oil processing and packaging [25]. Despite its imbalanced omega-6 to omega-3 ratio, cottonseed oil remains a valuable nutritional resource in regions with limited food alternatives (Figure 2)

Extraction Methods of Cottonseed Oil

There are two distinct methods usually used for extracting cottonseed oil. These two methods used for cottonseed oil extraction include mechanical pressing followed by solvent extraction whereas the second method involves cold pressing. Product certainty estimates and end-quality attributes together with product purity depend on the selection of extraction method [8].

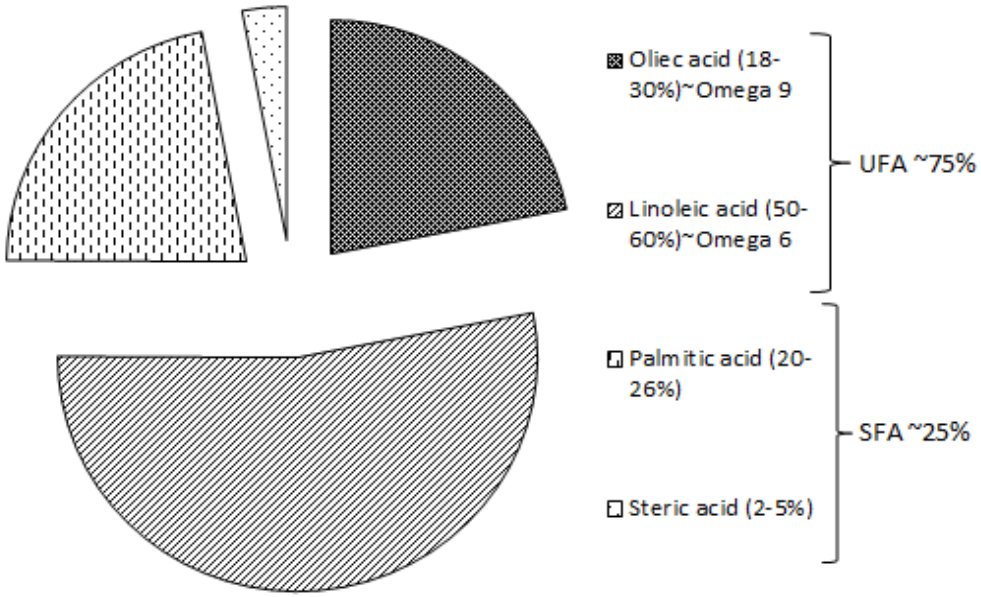

Figure 2 Fatty acid composition of cotton seed oil [53]

Physical Extraction Method

The physical extraction process of cottonseeds produces the end products of oil alongside seed cake [26]. The extraction process effectively conserves nutrients yet yields a lower extraction output compared to solvent extraction methods

Solvent Extraction Methods

Hexane extraction and its variant solvent extraction methods dominate the industrial process to extract 98% seed oil [8]. Cottonseed oil emerges through extraction since crushed cottonseeds absorb hexane solution before evaporating the liquid substance to produce clean cottonseed oil. Cottonseed oil extraction works efficiently with solvents but needs supplementary steps to eliminate all solvents along with impurities.

Cold Extraction Method

Cold pressing enables peak retention through its extraction method which operates at low temperatures thus preserving tocopherols antioxidants and essential fatty acids [27]. The commercial extraction method fails to produce enough oil for profitable use. Production of edible oil in refining plants removes harmful compounds which shorten shelf life by following degumming and neutralization into bleaching and deodorizing processes [28].

Refining Process

Cottonseed oil needs comprehensive refining for making it suitable for human consumption, various procedures are follows to remove both impurities with toxic substances alongside undesirable flavors from the oil [29]. Cottonseed oil requires various processing stages for remove gossypol (natural toxin) and additional impurity groups consisting of free fatty acids and phospholipids along with pigments and waxes [30]. The first step involves removing excessive gossypol, followed by degumming to extract phospholipids and gums. Next, neutralization eliminates free fatty acids, while bleaching removes color pigments. Deodorization then strips away flavor compounds and residual impurities. Finally, winterization prevents crystallization at low temperatures. The resulting refined oil is colorless, tasteless, and versatile for various applications [31].

The degumming process employs water and acidic chemicals to remove phospholipids and mucilage, enhancing oil clarity and stability [32]. After degumming, neutralization (alkali refining) purifies the oil further. Sodium hydroxide is added, triggering reactions that form soap stock, which is later separated. Activated carbon or clay adsorption then extracts pigments and heavy metals, improving brightness, purity, and color [33]. Product deodorization conducted by exposing distillates to steam under vacuum to extract volatile compounds alongside off-flavors that also eliminates gossypol for product neutralization and extended shelf life [10]. Winterization, a critical step in some refineries, prevents crystallization, making the oil suitable for salad dressings and margarine production [28]. Refineries use refinements on cottonseed oil to achieve product stability along with regulatory safety requirements suitable for industrial and commercial food use.

Health Benefits of Cottonseed Oil

Cottonseed oil combines a favorable fatty acid composition with strong antioxidant properties, offering multiple benefits for cardiovascular and metabolic health [19]. As a cholesterol-free oil, it is primarily composed of linoleic acid (50-60%), a polyunsaturated fatty acid (PUFA) known to help lower cholesterol levels and promote heart health [34]. Scientific studies confirm that PUFAs reduce the risk of coronary heart disease and atherosclerosis while improving lipid profiles and decreasing inflammation. Additionally, cottonseed oil contains vitamin E, which acts as an antioxidant, protecting cells and preventing lipid damage in body tissues [8]. According to researchers, incorporating cottonseed oil into a balanced diet can contribute to heart disease prevention [19].

Beyond cardiovascular benefits, cottonseed oil supports immune function, skin health, and metabolic regulation. Its high tocopherol content provides antioxidant, healing, and UV-protective properties, making it a valuable component in dermatological and cosmetic applications [35].

Recent studies about this oil identify the insulin-enhancing capabilities of polyunsaturated fatty acids coupled with phytosterols which supports diabetes prevention efforts for high-risk groups [36]. Furthermore, the plant sterols in cottonseed oil may help block intestinal cholesterol absorption, offering additional advantages for heart health [37]. While cottonseed oil provides essential fatty acids and

antioxidants, excessive omega-6 intake should be balanced with omega-3 to avoid inflammation. When used in moderation, it serves as a healthier alternative to saturated and trans fats in a balanced diet.

Potential Health Risks and Concerns

Due to unbalanced omega-6 to omega-3 ratio and toxic gossypol content which might not be effectively remove due processing difficulties possess significant health risks. More importantly, chronic inflammation can occur in individuals who consume cottonseed oil due to its extremely high linoleic acid (an omega-6 fatty acid) content, which exceeds Research indicates that an excessive intake of omega-6 over omega-3 contributes to cardiovascular diseases, arthritis, and metabolic disorders [38]. Commercial preparation of cottonseed oils undergoes hydrogenation treatment to maintain product stability and create unsafe trans fats which elevate LDL cholesterol alongside decreasing HDL cholesterol levels in the human body [19].

Another major concern is gossypol, a naturally occurring toxin in cotton plants that serves as an insect deterrent. Even trace amounts remaining after refinement can cause reproductive harm, liver damage, and anemia [39]. Research has proven that high levels of gossypol toxicant in unprocessed cottonseed oil cause reduced sperm movement and male infertility issues in human male reproduction. The extensive pesticide usage in cotton cultivation raises considerable concerns about non-organic cottonseed oil containing pesticide residues because these chemicals may eventually cause endocrine disruption and neurotoxicity. Consumers should restrict their dietary intake of authentic cottonseed oil to the point where its health risks are properly counterbalanced.

Industrial and Culinary Applications

The food industry along with industrial usage depends on cottonseed oil because of its lack of taste and ability to withstand high temperatures as well as its natural resistance to chemicals. The food processing industry employs cottonseed oil throughout its operations for deep-frying as well as baking production and salad dressing manufacturing and margarine making so it becomes fundamental in creating processed food meals and fast food items [40]. The product maintains resistance to oxidation and degradation at high temperatures of up to 232°C (450°F) which allows cottonseed oil to extend the preservation time of fried items [41]. Cottonseed oil appearance in light tones and flavor protection properties provide manufacturers with versatility to use it during snack food processing near mayonnaise and sweet food products [28]. Vitamin E (Tocopherol) in cottonseed oil increase its anti-oxidative properties to protect commercially packaged foods from spoilage thus increasing their total preservation duration [42].

The food sector is one of many industries where cottonseed oil serves as a key industrial ingredient. Beyond food production, it is utilized in biodiesel production, pharmaceuticals, cosmetics, and textiles. In cosmetics, cottonseed oil is valued for its emollient properties and antioxidant activities, making it a beneficial component in moisturizers, lotions, and soaps. These properties help enhance skin hydration and protect skin cells from oxidative stress. In biofuel production, cottonseed oil is converted into biodiesel, offering a sustainable energy alternative to fossil fuels and supporting eco-friendly power solutions [43]. Additionally, byproducts of cottonseed oil are repurposed as nutritious animal feed and environmentally friendly fertilizers, promoting sustainable agricultural practices.

Due to its diverse industrial and food applications, cottonseed oil has emerged as a driver of economic growth and environmental sustainability, holding significant commercial value.

Environmental and Sustainability Aspects

Cotton primarily serves as a textile material, but extracting oil from cottonseeds reduces agricultural waste, improve environmental sustainability together with resource conservation. The extraction of oil from cottonseeds improves waste reduction in agriculture and promotes economic opportunities [44]. Furthermore, by products obtained from processing of cottonseed such as cottonseed meal and hulls, contribute to the agricultural circular economy by being used as organic fertilizers and animal feed [30]. However, conventional cotton cultivation poses environmental risks due to excessive pesticide use and high water consumption. Addressing these challenges requires the simultaneous advancement of organic

cotton farming and genetically modified pest-resistant cotton varieties [45].

The production cycle of cottonseed oil also has environmental impacts, primarily through emissions, energy intensity, and solvent-based processing. For instance, hexane-based solvent extraction releases volatile organic compounds (VOCs) that often exceed environmental safety standards, attracting regulatory scrutiny [46]. Fortunately, advancements in mechanical pressing and sustainable refining technologies have helped mitigate these environmental concerns [47]. Additionally, cottonseed oil is gaining market traction as a renewable biofuel and biodiesel feedstock [48]. The cottonseed oil manufacturing industry continues to implement environmental conservation techniques that reduce water consumption and lower pesticide impact and facilitate organic product documentation [8]. Plant-based oil consumers are driving growth while requiring sustainable agricultural practices for cotton farming to combine with environmentally safe processing methods which minimize environmental footprints from cottonseed oil operations.

Recent Research and Future Trends

Modern scientific inventions of cottonseed oil extraction focus on innovative industrial methods and enhanced extraction methods and genetic approaches to boost oil yield. The study reveals GhHACD2 functions as a key regulator of very long-chain fatty acid synthesis for eventual genetic improvement of cottonseed oil production and quality enhancement. The research also highlights strategies for developing cotton cultivars with improved nutritional profiles, optimized oil production, and reduced gossypol content [49]. Additionally, scientists are exploring alternative extraction methods, such as supercritical carbon dioxide extraction combined with enzyme-assisted techniques, which provide environmentally friendly solutions [50]. The research community discovered nutraceutical applications of cottonseed oil because scientists proved its capacity to minimize inflammation while fighting oxidative stress.

The future applications of cottonseed oil focus on both sustainability goals and the creation of biofuel products along with functional meal development. Regulatory interest in non-GMO organic cottonseed oil has risen because consumers want plant-based oils and this drive led to pesticide-free sustainable agriculture practices [51]. The biofuel industry advancement requires renewable biodiesel materials which utilize cottonseed oil [48]. The application of nanotechnology for cottonseed oil stabilization using antioxidant nanocontainers to lengthen food storage durability [52]. Studies using biotechnology and agricultural solutions and green processing methods indicate cottonseed oil will become a leading choice for food security worldwide as well as sustainable energy solutions [53].

Conclusion

Cosmetic manufacturers together with industries and the food sector use cottonseed oil to fulfill their adjustable vegetable oil requirements. What draws many people to use cottonseed oil as their cooking medium is its ability to stay stable and high content of natural antioxidants along with unsaturated fats. People should exercise careful consumption of refined cottonseed oil because they remain worried about gossypol toxicity and excessive omega-6 content and pesticide contamination. Cottonseed oil retains its market value in the international sector thanks to improved biotechnology with sustainable agriculture practices and innovative food and energy applications. Futuristic scientific investigation needs to enhance nutritional content along with producing beneficial farming results through sustainable farming methods.

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