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Nutritional composition, functional properties, and value-added applications of date (*Phoenix dactylifera* L.) fruit and its by-products: A comprehensive review

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Abstract
Phoenix dactylifera L., commonly known as the date palm, is one of the oldest cultivated fruit trees, highly regarded for its nutritional, medicinal, and economic value. This review presents a comprehensive synthesis of the nutritional composition, bioactive compounds, and functional properties of date fruits and their by-products, particularly seeds. Dates are rich in natural sugars, dietary fiber, essential minerals, and phenolic compounds, offering potential health benefits including antioxidant, anti-inflammatory, cardioprotective, antimicrobial, and neuroprotective effects. The review highlights the valorization of underutilized parts of the date fruit, especially seeds, peels, and fibrous residues, into value-added products such as functional foods, nutraceuticals, cosmetics, and animal feed. Recent technological advancements, including supercritical CO_2 extraction, fermentation, encapsulation, and nanoformulation, have improved the stability, functionality, and commercial viability of these derivatives. Despite the promising applications, research gaps remain in the full-scale exploitation of underutilized varieties and the industrial-scale utilization of by-products. This review underscores the need for multidisciplinary research, sustainable processing innovations, and regulatory support to harness the full potential of *Phoenix dactylifera* L. for health, nutrition, and economic sustainability.

Keywords: *Phoenix dactylifera* L., date fruit, nutritional composition, functional properties, bioactive compounds, antioxidant activity, date seed, value-added products, by-product utilization, functional foods, food processing, sustainable agriculture

1. Introduction
Phoenix dactylifera L., commonly known as the date palm, is a perennial monocotyledonous plant belonging to the Arecaceae family. It has been cultivated for more than 5, 000 years, particularly in arid and semi-arid regions of the Middle East, North Africa, and South Asia (Al-Farsi & Lee, 2008) [2]. The date palm is renowned for its resilience to harsh climates and for producing nutrient-rich fruits, making it a vital component of food security and cultural heritage in date-producing regions (FAO, 2022) [20]. The global annual production of dates exceeds 9 megatons, with major contributions from countries such as Egypt, Iran, Saudi Arabia, and the United Arab Emirates (FAO, 2022) [20].
Dates are consumed in both fresh (rutab) and dried (tamr) forms and are celebrated for their high energy value and bioactive compounds. Beyond the edible pulp, the date seed, often treated as waste, has gained attention due to its substantial dietary fiber, phenolic content, and potential functional food applications (Platat *et al.*, 2014; Nejaty *et al.*, 2020) [29, 28]. The increasing demand for natural, functional, and sustainable food sources has positioned *Phoenix dactylifera* L. as a promising candidate for diversified applications in the food, pharmaceutical, and cosmetic industries.
The date palm (*Phoenix dactylifera* L.) is one of the oldest cultivated fruit trees, believed to have originated in the arid regions of the Middle East and North Africa (Al-Farsi & Lee, 2008) [2]. Revered for its nutritional richness, cultural importance, and medicinal uses, the date fruit has served as a staple food and an integral part of traditional diets in many parts of the world for centuries (Baliga *et al.*, 2011) [10]. With increasing interest in sustainable agriculture and functional foods, dates and their by-products have gained considerable

attention in recent years for their exceptional health benefits and industrial potential (Chaira *et al.*, 2007; Elleuch *et al.*, 2008) [14, 18].

Dates are naturally rich in carbohydrates, dietary fiber, essential minerals, and a variety of bioactive compounds, including polyphenols and antioxidants (Vayalil, 2012) [30]. These nutritional characteristics make them a valuable source of energy and a potential ingredient in therapeutic diets. In addition to the edible flesh, the seeds, skin, and other by-products of the date palm have shown promising uses in the development of nutraceuticals, food supplements, beverages, and cosmetic formulations, thus supporting the concept of zero-waste utilization (Al-Farsi *et al.*, 2005; Habib & Ibrahim, 2009) [4, 22].

2. Nutritional Composition of Date Fruits

The date fruit (*Phoenix dactylifera* L.) is highly valued for its rich and diverse nutritional composition, making it an important staple in arid and semi-arid regions of the world. Dates are primarily composed of carbohydrates, mainly in the form of glucose, fructose, and sucrose, which together constitute about 70-80% of the fruit's dry weight, depending on the variety and ripening stage (Al-Farsi & Lee, 2008) [2]. These natural sugars provide an immediate source of energy, making dates an ideal food for rapid energy replenishment.

Apart from their carbohydrate content, dates contain moderate amounts of protein (1.5-2.5%) and very low fat content (<0.5%), which contributes to their low lipid profile and cholesterol-free nature (Vayalil, 2012) [30]. The protein in dates is rich in essential amino acids such as lysine, leucine, and phenylalanine (Chaira *et al.*, 2007) [14]. Moreover, dates are an excellent source of dietary fiber, both soluble and insoluble, with total fiber content ranging from 6% to 11%, which supports digestive health and helps regulate blood sugar levels (Elleuch *et al.*, 2008) [18].

In terms of micronutrients, dates are notably rich in essential minerals including potassium, magnesium, calcium, iron, and phosphorus (Habib & Ibrahim, 2009; Ayad *et al.*, 2020) [22, 9]. Potassium, in particular, is present in high concentrations and plays a critical role in cardiovascular and muscular function. Furthermore, dates contain small but significant amounts of vitamins, particularly B-complex vitamins (such as B1, B2, B3, B6), vitamin A, and vitamin C, which support metabolic activities and antioxidant defence (Baliga *et al.*, 2011) [10].

Dates are also a rich source of bioactive compounds, especially polyphenols such as flavonoids, phenolic acids, and tannins, which exhibit strong antioxidant properties (Al-Farsi *et al.*, 2005) [4]. The concentration of these compounds varies depending on cultivar, processing, and ripening stages. These phytochemicals contribute to the fruit's functional properties, including anti-inflammatory, antimutagenic, and cardioprotective effects (Vayalil, 2012) [30].

The nutritional composition can vary widely among different cultivars. For instance, varieties such as Deglet Noor, Medjool, and Mazafati show notable differences in moisture content, sugar profile, and antioxidant activity, emphasizing the importance of cultivar-specific evaluations in research and product development (Biglari *et al.*, 2009) [13].

3. Functional and Bioactive Properties

Date fruit (*Phoenix dactylifera* L.) is widely recognized not only for its energy-dense nutritional composition but also for its rich profile of functional bioactive compounds. These compounds primarily polyphenols, flavonoids, dietary fiber, and carotenoids, contribute to a wide range of health-promoting effects, including antioxidant, anti-inflammatory, antimicrobial, and metabolic benefits (Baliga *et al.*, 2011; Vayalil, 2012) [10, 30].

3.1 Antioxidant Activity

Dates contain high levels of natural antioxidants such as phenolic acids (e.g., gallic, ferulic, and caffeic acids) and flavonoids (e.g., quercetin and luteolin), which play a critical role in neutralizing reactive oxygen species (ROS) and protecting cellular components from oxidative damage (Al-Farsi *et al.*, 2005) [4]. The antioxidant activity of dates has been shown to vary depending on variety, maturity stage, and postharvest handling. The antioxidant capacity of date fruits is strongly influenced by their cultivar and ripening stage (El Arem *et al.*, 2011) [17], with later ripening often enhancing polyphenol levels. Sun-dried and semi-dry varieties typically exhibit higher antioxidant content than fresh ones (Biglari *et al.*, 2009) [13].

3.2 Anti-Inflammatory and Cytoprotective Effects

Polyphenolic compounds found in date fruits exhibit anti-inflammatory properties by inhibiting pro-inflammatory enzymes such as cyclooxygenase (COX) and reducing cytokine activity. These mechanisms contribute to reduced inflammation and cellular stress in vital organs such as the liver and kidneys (Vayalil, 2012) [30]. Experimental studies have demonstrated the cytoprotective effects of date extracts in preventing lipid peroxidation and improving cellular integrity under stress conditions (Mohamed *et al.*, 2005) [26].

3.3 Antimicrobial Properties

Several *in vitro* studies have confirmed the antimicrobial activity of date extracts against common foodborne pathogens such as *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*. This antimicrobial efficacy is attributed to both the high sugar concentration in dates, which significantly lowers water activity (Aw), and the presence of tannins and polyphenols, which can disrupt microbial cell membranes. The study by Jdaini *et al.* (2022) [24] reported that microbial spoilage in dates is limited largely due to these intrinsic characteristics, including high sugar content and low Aw, alongside good post-harvest handling practices. Additionally, polyphenolic compounds found in date flesh and seeds are known to contribute to their antimicrobial and antioxidant properties.

3.4 Glycemic Control and Cardiometabolic Health

Although dates are high in natural sugars, they exhibit a relatively low to moderate glycemic index (GI), especially in semi-dry varieties such as Deglet Nour and Khalas. Studies suggest that the high content of dietary fiber and polyphenols in dates contributes to a slower absorption of glucose, thereby aiding in glycemic control and enhancing insulin sensitivity (Al-Farsi & Lee, 2008) [2]. Moreover, the antioxidant and anti-inflammatory properties of phenolic compounds in dates may further support metabolic health. Regular consumption of dates has also been associated with favorable effects on lipid profiles. Clinical and animal studies have reported reductions in total cholesterol, LDL cholesterol, and triglyceride levels, indicating potential benefits for cardiovascular risk management (Al-Farsi *et al.*, 2005; Baliga *et al.*, 2011) [4, 10].

3.5 Gut Health and Prebiotic Activity
Dates are a good source of both soluble and insoluble dietary fiber, with significant prebiotic potential. The fibers and associated polyphenols in dates stimulate the growth of beneficial gut microbiota such as *Lactobacillus* and *Bifidobacterium* species, contributing to improved digestive health and immune function (Elleuch *et al.*, 2008) [18]. These effects are beneficial in reducing the risk of gastrointestinal disorders, including constipation, irritable bowel syndrome, and colorectal cancer.

3.6 Neuroprotective and Anticancer Potential
Emerging research has highlighted the neuroprotective potential of date bioactives. Phenolic-rich extracts from dates have been reported to reduce oxidative stress and inhibit β-amyloid accumulation in neuronal tissues, which is associated with neurodegenerative diseases like Alzheimer's (Vayalil, 2012) [30]. In addition, flavonoids and phenolics in dates have shown antiproliferative and pro-apoptotic effects against various cancer cell lines *in vitro*, including colon and breast cancer cells, indicating their promise as natural anticancer agents (Hong *et al.*, 2006) [23].

4. Date Fruit By-products and Their Composition
In addition to the edible date flesh, the date palm tree yields several valuable by-products such as date seeds, skins, press cakes, and fibrous residues, which are often underutilized. These by-products contain significant nutritional and functional compounds, presenting opportunities for value addition and sustainable utilization in food, pharmaceutical, cosmetic, and industrial applications (Al-Farsi & Lee, 2008; Habib & Ibrahim, 2009) [2, 22].

4.1 Date Seeds
Date seeds, which account for approximately 10-15% of the total fruit weight, are the most prominent by-product of date fruit processing. Chemically, they are rich in dietary fiber (up to 80%), carbohydrates, and protein (5-7%), and contain 7-10% oil depending on the variety and extraction method (Besbes *et al.*, 2004) [11]. The oil extracted from date seeds is high in oleic acid, lauric acid, and linoleic acid, and contains tocopherols and phenolic compounds with strong antioxidant properties (Nehdi *et al.*, 2010) [27]. Moreover, date seeds are a source of polyphenols such as catechins, epicatechins, and procyanidins, contributing to their functional potential (Platat *et al.*, 2014) [29].

4.2 Date Seed Powder and Fiber
Date seeds, after drying and grinding, yield a fine powder that is increasingly used as a functional food ingredient. The powder is gluten-free, fiber-rich, and contains bioactive compounds suitable for incorporation in bakery, beverage, and nutraceutical products (Habib & Ibrahim, 2009) [22]. Due to their high insoluble fiber content, date seed powders support gut health and can be used as natural dietary supplements.

4.3 Date Press Cake and Fiber Residues
The residue left after juice or syrup extraction commonly known as date press cake contains fiber, sugars, and minor amounts of proteins and antioxidants. Though often discarded as waste, these residues have high potential for animal feed, composting, bioethanol production, and the development of fiber-rich food products (Chandrasekaran & Bahkali, 2013) [15]. The extraction of functional dietary fiber from date press cake is gaining attention as a means to utilize by-products in high-fiber formulations.

4.4 Date Skin and Peel Extracts
The outer skin of the date fruit, typically removed during processing, is another by-product rich in antioxidants. It has been shown to contain higher concentrations of phenolic compounds than the fruit pulp itself. Extracts from the peel exhibit notable antioxidant and antimicrobial activity, making them suitable for use as natural food preservatives and functional additives (Al-Farsi *et al.*, 2005) [4].

5. Value-Added Applications
The economic and nutritional potential of *Phoenix dactylifera* L. has led to the development of various value-added products from both its edible fruit and processing by-products. These innovations not only enhance consumer acceptability and nutritional intake but also support sustainability by minimizing agricultural waste. From functional foods to cosmetics and animal nutrition, the applications of dates and their derivatives are growing rapidly.

5.1 Food and Confectionery Products
Dates are widely processed into products such as jams, syrups, pastes, bars, and bakery ingredients. Due to their high sugar content and natural binding properties, date pastes are used as sweeteners and fat replacers in cakes, cookies, and energy bars (Al-Farsi & Lee, 2008) [2]. Date syrup, a natural alternative to refined sugar, is used in beverages and sauces, offering both sweetness and antioxidant benefits (Al-Farsi *et al.*, 2007) [3]. Moreover, the inclusion of date flour in bakery products has been shown to enhance the fiber, mineral, and antioxidant content without compromising sensory attributes (Baliga *et al.*, 2011) [10].

5.2 Fermented Functional Beverages
The natural sugars and fibers in dates provide an excellent substrate for fermentation. Date-based beverages, including probiotic drinks, non-dairy kefirs, and fermented syrups, have been developed for health-conscious and lactose-intolerant consumers. These products not only deliver energy but also offer probiotic and prebiotic benefits by supporting the growth of beneficial gut microbiota (Al-Juhaimi *et al.*, 2020) [7]. The prebiotic nature of date fibers, particularly those from date seeds and pulp, further enhances their role in gut health and immune support.
"Date-derived substrates support probiotic and even ethanolic/acidic fermentations for non-dairy beverages due to intrinsic sugar, fiber, and phenolics. Studies show Lactobacillus spp. flourish in date syrup, and date waste is fermentable to bioethanol or vinegar-style drinks" (Ahmad *et al.*, 2021; Karbasi *et al.*, 2015) [1, 25].

5.3 Nutraceutical and Therapeutic Products
Bioactive-rich date seed powder and extracts are used in nutraceuticals for their antioxidant, anti-inflammatory, and al glycemic regulatory properties. Polyphenol-rich capsules and powders derived from date seeds are marketed for cardiovascular and metabolic health. Functional food formulations containing date derivatives also help in reducing oxidative stress and improving overall wellness (Platat *et al.*, 2014; Vayalil, 2012) [29, 30].

5.4 Cosmetic and Personal Care Applications

Date seed oil is gaining recognition in the cosmetics industry due to its rich composition of oleic acid, tocopherols, and phytosterols. It is used in products like skin moisturizers, hair oils, anti-aging creams, and sunscreens for its antioxidant and emollient properties (Nehdi *et al*., 2010) [27]. Additionally, extracts from date peels and seeds are included in exfoliating scrubs and face masks for their skin-renewal and antimicrobial benefits.

5.5 Animal Feed and Industrial Applications

Date seed meal (DSM) and pulp residues are promising ingredients in livestock and poultry diets. Recent studies have shown that inclusion of DSM up to 10% can improve feed conversion ratio (FCR), body weight gain, and nutrient digestibility in broilers without adverse effects (Attia *et al.*, 2023) [8]. Moreover, the use of 1-2% date seed powder in poultry diets improved meat quality and antioxidant activity (Al-Saffar & Al-Mola, 2010) [5]. Fermented date waste has also been explored for bioethanol, biogas, and organic acid production, supporting circular bioeconomy goals (Chandrasekaran & Bahkali, 2013) [15].

6. Recent Advances in Processing Technologies

Elwakeel *et al.* (2022) [19] describe a range of drying techniques, including open sun drying, solar dryers, hot air ovens, freeze drying, drum drying, microwave drying, and spray drying. It emphasizes that sun drying is economical but leads to poor quality due to contamination and uncontrolled conditions, while industrial drying methods (e.g., hot air and freeze drying) maintain better nutritional and physical qualities, with freeze drying offering superior retention of bioactives and sensory properties due to low processing temperatures

Advanced extraction techniques have significantly improved the recovery and quality of bioactive compounds from date seeds. While traditional solvent extraction methods such as Soxhlet are still commonly used, they often involve prolonged exposure to heat and toxic solvents, which may degrade sensitive compounds and leave residues. In contrast, supercritical fluid extraction (SFE) using carbon dioxide (CO_2) has emerged as a green, efficient alternative that operates under mild conditions, thereby preserving the functional integrity of phenolics and oils. According to Nehdi *et al.* (2010) [27] and Besbes *et al.* (2004) [11], SFE effectively extracts date seed oil rich in oleic acid, tocopherols, and polyphenols, making it suitable for nutraceutical and cosmetic applications. Furthermore, recent studies by Al-Dhabi *et al.* (2022) [6] demonstrate that subcritical CO_2 extraction ($SubCO_2$) yields significantly higher concentrations of phenolics (227.93-274.98 mg GAE/100 g) and flavonoids (98.01-141.78 mg QE/100 g) compared to Soxhlet methods, highlighting its superior efficiency and eco-friendliness. These advancements underscore the growing potential of CO_2-based extraction systems in developing high-value, antioxidant-rich date seed products.

Furthermore, innovations such as encapsulation, fermentation, and nanoformulations are being applied to enhance the functionality and stability of date-derived compounds. Microencapsulation using carriers like maltodextrin can protect phenolics during processing and storage. Fermentation of date pulp with probiotic cultures increases bioavailability and gut health benefits. Nanoformulations are also being explored for targeted delivery of antioxidants in nutraceuticals (Platat *et al.*, 2014) [29].

Packaging innovations have played a crucial role in extending the shelf life of date-based products. Technologies such as vacuum packaging, modified atmosphere packaging (MAP), and the use of active packaging materials with antimicrobial properties have demonstrated effectiveness in preserving quality attributes such as color, texture, and microbial stability (Jdaini *et al.*, 2022) [24]. These advances ensure longer shelf stability and reduced postharvest losses, supporting commercial scalability. Adhering to international hygiene guidelines such as those outlined by the Codex Alimentarius Commission (2003) [16] is essential for ensuring the microbiological quality and consumer safety of date-based products.

7. Chronological Development of Dates and Date Seeds

The cultivation and utilization of the date palm (*Phoenix dactylifera* L.) span over 5, 000 years, making it one of the oldest domesticated fruit trees known to humankind. Archaeological evidence traces its origin to the arid regions of Mesopotamia (modern-day Iraq) and North Africa, where dates were integral to ancient agricultural systems and diets (Al-Farsi & Lee, 2008) [2]. References to date cultivation can be found in Sumerian texts, Egyptian tombs, and classical writings, underscoring the fruit's historical and cultural significance. Revered not only for their energy-dense nutritional value but also for their long shelf life and portability, dates were considered a staple food among nomadic tribes, caravan traders, and desert dwellers. Their high sugar content and resilience against spoilage allowed for long-distance transport and storage, further solidifying their role in early food systems.

Traditionally, only the edible pulp of dates was utilized for human consumption, either in fresh (rutab) or dried (tamr) forms, or processed into syrups, pastes, and confections. Meanwhile, the seeds, which account for approximately 10-15% of the total fruit weight, were often discarded or used as animal feed with minimal value addition. However, advancements in analytical techniques and growing emphasis on food sustainability have led to a paradigm shift in how date seeds are perceived and utilized.

In the past two decades, scientific studies have highlighted the nutritional and functional potential of date seeds, showing that they are rich in bioactive compounds such as phenolics, flavonoids, and dietary fiber, along with valuable oils (Platat *et al.*, 2014; Bettaieb *et al.*, 2023) [29, 12]. Their antioxidant, antimicrobial, and anti-inflammatory properties make them promising candidates for health-promoting products, contributing to the development of functional foods, nutraceuticals, and therapeutic formulations. As a result, date seed powder is now commonly used in high-fiber bakery products, as well as in caffeine-free date seed coffee, a sustainable alternative to conventional coffee (Bettaieb *et al.*, 2023) [12]. Additionally, the cosmetic industry has begun incorporating date seed oil for its emollient, anti-aging, and skin-nourishing effects (Nehdi *et al.*, 2010) [27].

Technological advancements, particularly in extraction and preservation methods, have played a pivotal role in unlocking the potential of date seeds. Processes such as supercritical CO_2 extraction allow for the recovery of high-

quality oils and phenolics without harmful solvent residues, enhancing safety and commercial feasibility (Al-Dhabi *et al.*, 2022) [6]. Post-harvest drying methods like freeze drying and solar drying have further improved the retention of bioactives in both pulp and seed derivatives, thereby extending shelf life and ensuring microbiological safety (Elwakeel *et al.*, 2022; Jdaini *et al.*, 2022) [19, 24].

Moreover, innovations such as microencapsulation, fermentation, and nano-formulation have enabled the incorporation of date seed extracts into more advanced applications, ranging from probiotic foods to targeted drug delivery systems. Research is also increasingly focused on developing standardized extraction protocols and assessing the functional stability of bioactives during processing and storage, aiming to integrate date seed derivatives into mainstream consumer products.

This evolving trajectory reflects a broader movement toward agricultural waste valorization and circular bioeconomy. The transition of date seeds from a low-value by-product to a premium functional ingredient exemplifies how traditional agricultural systems can adapt to modern sustainability challenges. As global demand grows for natural, plant-based, and functional ingredients, the chronological journey of *Phoenix dactylifera* from staple food to nutraceutical powerhouse underscores its enduring value in both traditional and modern food systems.

8. Future Prospects and Research Gaps

8.1 Exploration of underutilized varieties

While major commercial varieties such as Medjool, Khalas, and Deglet Noor dominate global date markets, a significant number of underutilized and indigenous date cultivars remain poorly studied and economically neglected. These lesser-known varieties, often cultivated in remote or marginal regions, may possess unique nutritional, functional, and agronomic traits such as higher antioxidant levels, drought resistance, or distinct flavor profiles. However, due to limited characterization, inadequate postharvest handling, and lack of market access, their commercial potential remains untapped (Al-Farsi & Lee, 2008; Elwakeel *et al.*, 2022) [2, 19].

Future research should focus on comprehensive profiling of these cultivars, including their bioactive compound composition, phytochemical properties, and suitability for value-added applications such as natural sweeteners, dietary supplements, or fermented products. Additionally, genomic and metabolomic tools could be employed to better understand the genetic diversity and functional attributes of underutilized varieties. Such studies would not only contribute to biodiversity conservation but also support agricultural sustainability and rural livelihoods by opening new markets for traditional cultivars. Bridging this research gap through interdisciplinary collaboration is essential to harness the full potential of the date palm's genetic wealth in both food and non-food sectors.

8.2 Scaling up sustainable by-product utilization

The growing emphasis on sustainable food systems has spotlighted the importance of fully utilizing agro-industrial by-products such as date seeds, peels, and processing residues. Despite numerous studies highlighting the nutritional, antioxidant, and functional properties of date by-products, large-scale industrial utilization remains limited. A key challenge is the scaling up of advanced processing technologies, such as supercritical CO_2 extraction and microencapsulation, which, while effective, require significant capital investment and technical expertise (Besbes *et al.*, 2004; Ghafoor *et al.*, 2022) [11, 21]. Moreover, there is a lack of standardized protocols and regulatory clarity for incorporating these components into mainstream food, nutraceutical, and cosmetic formulations.

To bridge this gap, future research should focus on the development of cost-effective, energy-efficient, and scalable extraction techniques that preserve the functional integrity of date-derived bioactives. Simultaneously, building value chains for products like date seed flour, oil, and antioxidant-rich extracts combined with consumer awareness and supportive policy frameworks can help transition these by-products into viable commercial ingredients. Incorporating life cycle assessments (LCA) and circular economy models will further strengthen the sustainability of the date industry. In this context, scaling up sustainable by-product utilization stands as a pivotal opportunity to reduce agri-waste, promote health-focused innovation, and align with global environmental targets.

9. Conclusion

The date palm (*Phoenix dactylifera* L.) represents a highly versatile and sustainable crop with far-reaching benefits in nutrition, health, and industry. Rich in carbohydrates, fibers, essential nutrients, and potent bioactives, date fruits offer considerable functional and therapeutic potential. Importantly, their by-products, particularly seeds, skins, and press residues hold untapped value for developing health-promoting foods, cosmetics, and bio-based industrial applications. Technological advances in drying, extraction, and formulation techniques have enhanced the efficiency and functionality of these products. However, the commercialization of such innovations faces challenges, including cost-effective processing, regulatory standardization, and limited characterization of underutilized cultivars. Future research should prioritize scaling up sustainable technologies, exploring genetic diversity, and integrating circular economy principles. A strategic, interdisciplinary approach will be critical to unlock the full potential of date fruits and their derivatives, enabling their transformation from traditional staples into globally relevant functional and therapeutic ingredients.

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