







Review

Advancing Sustainable Utilization of Date Palm, *Phoenix dactylifera*, a Multifunctional Resource for Agro-Industrial Applications

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Abstract: The date palm (*Phoenix dactylifera* L.), a versatile crop in arid regions, offers immense potential beyond its edible fruit. Rich in compositions of carbohydrates, dietary fibers, proteins, vitamins, and antioxidants, dates are widely consumed, while other plant parts (seeds and leaves) are frequently overlooked. Traditionally discarded or repurposed to low-value uses like animal feed, these by-products possess untapped potential for high-value applications. Hence, this review presents comprehensive analysis of multifunctional applications of date palm resources, emphasizing their role in bioproduct developments as food, cosmetics and pharmaceuticals. A key innovation of this work lies in its holistic approach to date palm utilization, framed within the context of the circular bioeconomy. In addition to product-oriented applications, this review introduces a novel concept of using date palm as biomonitoring and bioremediation agent. The plant's physiological responses to environmental pollutants and contaminants position it as a promising tool for environmental assessment and remediation. This dual-purpose role enhances the eco-logical and economic value of the date palm. This review also examines traditional and modern irrigation systems used in date palm cultivation, comparing their efficiency, adaptability, and sustainability. Furthermore, this review identifies research challenges, including the need for standardization of extraction and processing methods, as well as outlines future directions for enhancing the global impact of date palm-based biorefineries, particularly through the integration of precision irrigation and remote sensing. This review contributes original insights to the evolving discourse on sustainable resource utilization, positioning the date palm as a climate-resilient, low-waste innovation model crop.

Keywords: *Phoenix dactylifera*; date palm; antioxidant; irrigation; biomonitoring



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1. Introduction

Date palm (*Phoenix dactylifera* L.; family: Arecaceae or Palmae), is among the earliest man-cultivated tree species (Al-Mssallem et al., 2013), especially prominent in regions, for instance, the Arabian Peninsula (United Arab Emirates, Saudi Arabia, Oman, Jordan), Iran, Pakistan, and the United States, because it can endure challenging environments with diverse temperatures, salinity, water scarcity and arid climate conditions. Statistically, over 5,000 varieties of date palm species have been documented globally.

Symbolised as life in the desert, the date palm is morphologically characterised by a growing height of up to 20 m and distinguished by features of feather-like leaves with fibrous extensions radiating from a central crown. Its fruit is nutritionally rich, containing a diverse spectrum of functional compounds, for example, carbohydrates, dietary fibres, minerals, vitamins, and antioxidants. Beyond its fruit, different sections of the tree are utilised in traditional and modern applications: the trunk and the leaf midribs serve as materials for infrastructure and biofuel production; fronds are utilised for the building of roofs and huts; leaflets are crafted into baskets and mats; and the

coarse fibres around the leaf bases (known as fibrillum) are repurposed into ropes, packaging and padding. Moreover, date palm also plays a role in environmental monitoring. It has been employed as a biomonitor to assess heavy metal accumulation and air pollution in specific regions (Al-Khashman et al., 2011; Al-Khlaifat & Al-Khashman, 2007; Al-Shayeb et al., 1995; Jafari et al., 2023; Tengberg, 2012).

Date palm fruit is highly valued for its rich nutritional and medicinal attributes. Unique among fruits, it has served as a dietary staple for thousands of years, sustaining millions of people across various cultures. Archaeological evidence from sites such as Sabiyah in Kuwait and Dalma Island in the UAE reveals early consumption of dates, as indicated by the discovery of carbonised seeds and stones (Ahmed et al. 2013; Tengberg, 2012). In Islamic tradition, dates hold special significance, especially prominent during the sacred month of Ramadan, as they are commonly served as customary food in iftar practices for breaking the daily fast, a practice dating back to the time of Prophet Mohammed (Peace Be Upon Him) and referenced in the Holy Quran (Al-Dashti et al., 2021). One of the remarkable features of date palm fruit is its edibility across three progressive ripening phases: khalal (fresh and firm), rutab (soft and succulent), and tamar (fully ripe; Al-Mssalem et al., 2013). The transition to the tamar stage typically occurs 150 to 200 days post-pollination, at which point the fruits develop dark colouration with a tender and chewy mouthfeel. In this period, the fruits contain a high number of natural sugars, for instance, fructose, glucose, and sucrose. This stage also marks the lowest moisture content, making the fruit ideal for long-term storage (Aleid et al., 1999; Sawaya et al., 1983).

Dates hold a prominent cultural and social significance in the Middle Eastern nations and among Arab communities. They are traditionally served during important occasions, including weddings, birth celebrations, communal gatherings, festive occasions, and religious celebrations. Fresh dates are especially prized for their flavour and texture. The market offers a wide range of date-based products, such as homemade delicacies, pastries, baked goods, confectioneries, beverages, date paste, flour, jams, milk, ice-cream, syrup, and even fermentation items like wine, alcohol, and organic acids. Despite their well-known nutritional and therapeutic benefits, dates remain underappreciated in other parts of the world. This is partly due to limited scientific literature, much of which is rooted in Islamic prophetic traditions (Vayalil, 2012; Zaid & de Wet, 1999).

Globally, date cultivation is a significant agricultural sector, with an annual production of approximately 5.4 million metric tonnes. Over the past decade, the industry has grown by approximately 18%, yielding 8.53 million metric tons across 1.11 million hectares of farmland (Alotaibi et al., 2023). In 2001, five countries (Egypt, Iran, Saudi Arabia, Pakistan, and Iraq) accounted for nearly 69% of the world's date output. Including Algeria, the UAE, Sudan, Oman, and Morocco raises this figure to 90%, highlighting the regional concentration of date farming (Botes & Zaid, 1999). Arab countries collectively have more than 85 million cultivated date palm trees, with the highest concentrations found in regions such as Saudi Arabia, UAE, Tunisia, Morocco, Algeria, Iran, Iraq, and Egypt (Al-Omran et al., 2019), making these nations central to global date palm cultivation. Recent data indicate that Saudi Arabia cultivates over 28 million date palms across approximately 160,000 hectares. This extensive cultivation supports nearly 120,000 farms, which collectively contribute around 55% of the nation's total date fruit production (Mansour & Chockalingam, 2020). In Qatar, date palms are the most extensively grown fruit trees, contributing approximately 7.2% to the country's total agricultural output (Islam et al., 2020).

Date palms can be replenished within a relatively short period. After planting, these trees typically begin fruiting in 4 to 8 years, and consistent yields suitable for commercial use are usually achieved within 7 to 10 years (Al-Dakheel et al., 2022; Alnaim et al., 2022). Primarily grown in the hot, arid zones of Southwest Asia and North Africa, dates are marketed worldwide as a premium fruit and confectionery crop. They also remain a vital subsistence food in desert regions. Recent years have seen growing scientific interest in the potential health benefits of dates, prompting numerous laboratory and animal-based studies focused on their phytochemical composition. Scientific evidence suggests that dates are a rich source of nutrients and are believed to support overall well-being. Despite their naturally elevated sugar content, many date varieties have a low glycemic index, challenging the misconception that dates are comparable to candy and contribute to chronic diseases.

While several reviews have been published on the nutrient profile and associated health impacts of dates, a significant gap remains in the literature regarding the comprehensive valorisation of date by-products, particularly date seeds, within the context of bioproduct development and waste management. Existing literature tends to focus predominantly on dietary aspects, leaving a gap in understanding the multifunctional applications of these underutilised resources. The innovation of this review lies in the novel and multidisciplinary perspective on the utilisation of date palm components within the framework of the circular economy, integrating its applications in pharmaceutical and environmental domains. Hence, this review introduces several key breakthroughs. First, it explores the underutilised potential of date palm by-products, especially date seeds, in the

development of high-value products, supported by relevant metrics, and explores their role in advancing circular bioeconomy and biorefinery models. More comprehensive exploration is necessary to validate their health potentials, elucidate mechanisms of action, and establish their role as a functional and medicinal food globally (Vayalil, 2012). Secondly, this review explores the use of date palms in environmental monitoring, particularly for detecting heavy metal accumulation and air pollution, an area rarely addressed in existing review studies. Third, this review also compares the traditional irrigating system, highlighting the role of emerging irrigation technologies to enhance water-use efficiency and support climate-resilient agriculture. Finally, we discuss current challenges and future research directions for expanding the global utilisation of date palms.

2. Methodology

This review aims to assess recent literature to address the research question concerning the multifunctional applications of date palm components, especially date seed in bioproducts development and environmental remediation. A systematic literature search is conducted using several academic databases, including Google Scholar, Web of Science, and Scopus, to identify relevant research and review articles on *Phoenix dactylifera* or date palm on the aspects of biomedical, agricultural, and environmental sciences. Databases such as Web of Science and Scopus are recognised for their selective indexing of peer-reviewed research, ensuring scholarly rigour and credibility. In contrast, Google Scholar offers a wider range of sources, including unpublished manuscripts, conference proceeding papers, and other academic materials, such as these, dissertations, technical reports, institutional repositories, and book chapters. The search includes studies published in English from 2000 to 2025, without predefined date restrictions. The search strategy is developed using keywords related to date palm, for example: (“date palm” OR “*Phoenix dactylifera*”) AND (“nutritional value” OR “medicinal properties” OR “bioremediation” OR “irrigation” OR “biochemical composition” OR “health benefits”). The initial search yields a large volume of records in terms of academic journals, theses, dissertations, book chapters, and conference proceedings, which are then screened in multiple stages. First, deduplication of records across databases, followed by screening of titles and abstracts for relevance, and lastly, full-text articles are retrieved for those meeting the criteria to confirm eligibility based on the inclusion criteria. The studies are included based on the inclusion criteria, including focus on *Phoenix dactylifera*, date palm in the context of cultivation (traditional and modern approaches), application of various date palm components (bioproducts synthesis and bioremediation), experimental or modelling studies, published in English and accessible in full text. Studies that were conceptual, outside the defined timeframe, lacking methodological rigour, non-English articles, inaccessible full texts, or focused on unrelated topics were excluded. The extracted data are further synthesised through content analysis, allowing for classification into a few sections. These include irrigation systems, bioproduct valorisation of date palm components (fruits and seeds), date palm as the bioremediation agent, challenges, and future research directions. Acronyms and technical terminology are clearly defined in the nomenclature section to ensure clarity and consistency throughout the analysis. The challenges identified in the literature are categorised into thematic areas, including technological barriers, resource constraints, and gaps in knowledge related to bioproduct valorisation. Each challenge is further analysed to uncover underlying causes and potential avenues for future research. The findings are organised and illustrated using tools, such as figures and tables, to enhance comprehension of current trends. This approach highlights the economic value of date palm cultivation and its associated bioproducts.

3. Irrigation Management - Date Palm Cultivation

Due to their drought tolerance and high resilience in dry climates, date palms are a suitable choice for farming in water-constrained regions, particularly during the mid to late growing seasons. Unlike many traditional winter crops, it can thrive with minimal irrigation and in saline conditions, making it an ideal choice for arid and semi-arid environments. Furthermore, their flexibility in soil requirements, including sandy, saline, and calcareous soils, allows date palms to be cultivated in a broad spectrum of terrains without competing with other seasonal crops (Ghazzawy et al., 2022). Climate is a key determinant in the successful cultivation and productivity of date palms. Key environmental factors, for example, temperature, rainfall, humidity, sunlight, and wind, significantly influence the suitability of a location for successful date palm cultivation.

Efficient irrigation is essential for the healthy growth and successful production of date palms, particularly within oasis agroecosystems. Table 1 illustrates various irrigation systems used for date palm farming. Understanding the root distribution of date palms is essential for effective water management. When soil is separated into four equal horizontal layers, root distribution tends to be uneven across soil depths, with the majority, around 40%, located in the uppermost layer of the soil profile. The concentration gradually decreases with depth, with approximately 30% in the second

layer, 20% in the third, and only 10% reaching the deepest section. Water uptake mirrors this distribution, with the majority absorbed from the upper soil layers.

Table 1. Different irrigation methods of date palm farming (Liebenberg & Zaid, 1999).

Irrigation method	Description	Advantages	Disadvantages
Flood irrigation	The oldest and most widely practised method	<ul style="list-style-type: none"> - Low operational cost - Ease of implementation - Cheap installation cost, especially in relatively flat terrains 	<ul style="list-style-type: none"> - Low efficiency - Labour-intensive - Non-targeted irrigation, which leads to wastage - Unsuitable for sandy soils
Furrow and basin irrigation	An improved version of flood irrigation designed to address its limitations	<ul style="list-style-type: none"> - Low operational cost - Ease of implementation - Cheap installation cost, especially in relatively flat terrains 	<ul style="list-style-type: none"> - High labour requirements - Disruption of mechanized farming
Sprinkler irrigation	Recognised as one of the earliest modern irrigation methods, it is developed to enhance water efficiency and support the automation of agricultural processes	<ul style="list-style-type: none"> - Efficient water usage - Simplified scheduling and management - Reduced labour requirements - Adaptability to terrain, even in areas with uneven or challenging topography 	<ul style="list-style-type: none"> - High installation cost - Elevated operational expenses - Sensitivity to environmental conditions - Unsuitability for young palms
Micro irrigation	Originally developed in South Africa to stabilise mine dumps by preventing wind erosion of sand, it is later adapted for agricultural use, particularly for irrigating trees and various crops.	<ul style="list-style-type: none"> - Efficient water usage - Lower operational costs - Easy to schedule and manage by automation - Targeted watering - Topography flexibility - Low labour demand - Customizable spray patterns 	<ul style="list-style-type: none"> - High installation costs - Requires clean water Affected by environmental conditions
Drip irrigation	The most recent advancement in irrigation technology was developed in Israel, specifically designed to maximise water efficiency in agriculture under conditions of scarcity.	<ul style="list-style-type: none"> - High efficient water use - Low operational costs - Low labour demand - Simple management - Targeted application - Terrain flexibility - Automation-friendly - Customizable spray patterns 	<ul style="list-style-type: none"> - High installation costs - Strict water quality requirements to prevent clogging - Monitoring challenges

For mature date palms, the root system typically extends to a depth of around 5 meters and spreads within a 3-meter radius from the trunk. Water extraction is most efficient in the top 150 cm of soil—40% absorbed within the first 50 cm, 70% from the top 100 cm, and 90% from the top 150 cm. Beyond this point, water uptake drops sharply, contributing only about 10%. In contrast, young date palms have a much shallower root system, typically extending 25 to 50 cm deep and spreading laterally within a 10 to 30 cm, which varies according to the size of the individual plant.

Therefore, irrigation must be carefully targeted within these zones to ensure water reaches the active root area. Over-irrigation that penetrates deeper soil layers can hinder proper root development. Localized irrigation techniques, for example, drip or micro-irrigation, are more efficient and suitable than traditional flood irrigation. For newly planted tissue culture-derived date palms, the portion of soil accessible for water uptake is minimal, necessitating frequent and precise watering. Extra attention is required when planting in sandy soils, which have low water retention capacity (Liebenberg & Zaid, 1999).

Water delivery methods for date palm cultivation vary depending on local hydrological conditions, available technology, and traditional practices. Today, mechanical pumping from underground water sources via wells is widely used. Historically, water was raised using manual or

animal-powered devices such as the Egyptian shaduf, a technique common in the ancient Near East. Additionally, water was transported from rivers or distant aquifers through open channels or underground systems like the falaj or qanat, which reflect the ingenuity of traditional irrigation infrastructure (Costa, 1983; Eyre, 1994). These systems involve channeling groundwater through a network of tunnels and conduits to irrigate date palm plantations. Widely used across the Middle East and North Africa, they exemplify the ingenuity of traditional water management practices developed to support agriculture in arid and desert climates, particularly in Middle Eastern countries.

The natural tolerance of date palms to heat and drought makes them a strategic crop for food production. The study by Allbed et al. (2017) demonstrated a notable decrease in the climate compatibility required for successful date palm cultivation, driven by shifting weather patterns and rising temperatures. Drought, which is influenced by fluctuations in temperature and rainfall patterns, affects date palm in a multifaceted way, as shown in Figure 1 (Akenous et al., 2022). Investigation of drought stress on the physiological and biochemical responses of four date palm cultivars (Khalas, Barhee, Hilali, and Ashrasee) in arid conditions revealed that severe drought diminished leaf formation, reduced biomass yield, and impaired physiological performance (Khalas and Barhee cultivars demonstrated greater drought tolerance, whereas Ashrasee was the most sensitive), highlighting the potential of deficit irrigation and cultivar selection as strategies for conserving water and maintaining productivity in arid agriculture (Ali-Dinar et al., 2023). Date palms require adequate irrigation with good-quality water to reach their full yield potential (Allbed et al., 2017). Hence, emerging technologies, such as sensor-driven irrigation systems, offer a more sustainable alternative by optimizing water use and maintaining productivity. Mohammed et al. (2021a) developed a fully automated subsurface irrigation system (CSIS) to remotely manage water use for date palm cultivation. Using sensors and the ThingSpeak cloud platform, this system monitored climate and soil moisture in real time, enabling precise irrigation scheduling. The sensor-based method (S-BIS) demonstrated greater effectiveness compared to the time-based scheduling (T-BIS), targeting irrigation to the root zone when plants can most effectively utilize it. In contrast to conventional surface irrigation, CSIS methods significantly reduced water usage by approximately 60%, improving water productivity and maintaining soil moisture near field capacity. These results highlighted CSIS with S-BIS as a promising solution for sustainable date palm irrigation in arid regions (Mohammed et al., 2021a). Mohammed et al. (2021b) also evaluated the effects of controlled deficit irrigation using drip (DI) and subsurface (SI) micro-irrigation systems on water use efficiency, gas exchange, yield, and fruit quality of Khalas date palms. Conducted over two seasons at King Faisal University, the research used IoT-based monitoring to guide irrigation scheduling at 50%, 75%, and 100% of crop evapotranspiration (ET_c), compared to conventional surface irrigation. Results showed that SI consistently outperformed DI, especially at the 50% ET_c level, as well as maintained fruit quality comparable to full irrigation, reducing water use. In short, high efficiency in managing irrigation is essential for widespread adoption in date palm cultivation across countries with arid and semi-arid climates. Modern irrigation systems for date palm cultivation using sensors and the Internet of Things represent a significant shift from traditional irrigation methods. These technologies not only improve water-use efficiency but also align with the principles of sustainable utilization and the circular bioeconomy by minimizing resource waste and optimizing input-output ratios. The adoption of irrigation methods needs to focus on their cost-effectiveness and scalability. Regional variations in the use of irrigation methods are often influenced by policy incentives, infrastructure, and farmer awareness. However, a critical gap remains in the integration of real-time data analytics and IoT-based monitoring. Future research should focus on developing adaptive irrigation models tailored to arid climates, incorporating recycled water sources with low capital and operational costs, thereby reinforcing the circular bioeconomy framework in date palm farming.

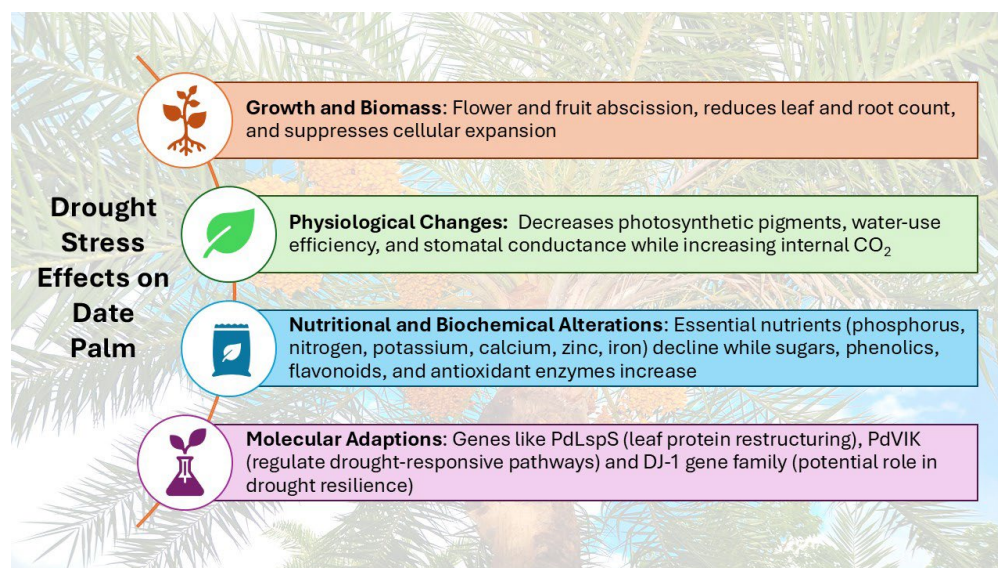


Figure 1. Impact of drought stress on date palm. Adapted from Akenous et al. (2022).

4. Date Palm Components

This section provides a comprehensive overview of the two primary components of the date palm that are of nutritional and medicinal interest: the date palm fruit (Section 4.1) and the date palm seed (Section 4.2). Each subsection explores the unique characteristics of these components, focusing on their nutritional composition, health benefits, and medicinal properties. By analyzing both the fruit and seed separately, this section aims to highlight their distinct contributions to human health and their potential for value-added applications in different industries.

4.1. Fruit

Globally, over 600 distinct varieties of date palm have been identified, each differing in shape, taste, and other sensory attributes. Some well-known cultivars include Ajwah, Medjool, Deglet Noor, Barhi, Zahidi, Khadrawy, and Fard, among many others cultivated across various regions (Al-shahib & Marshall, 2003; Chaira et al., 2009; Chandra et al., 1992; Habib & Ibrahim, 2009). The fruiting cycle of the date palm occurs annually and involves five developmental stages following pollination, culminating in full ripeness over approximately seven months. Ripe dates typically range in colour from yellow to reddish-brown and grow in large clusters. Each bunch can weigh up to 10 kg, and a mature palm may produce around ten bunches per season, yielding approximately 100 kg of fruit (Zaid, 2024). The date fruit is composed of two main parts: the edible pulp and the seed (also referred to as the pit or kernel). The pulp accounts for approximately 85–95% of the entire fruit weight (Bentrad & Hamida-Ferhat, 2020; Mrabet et al., 2019), while the seed makes up the remaining 5–15%, depending on the variety (Fernández-López et al., 2022).

Dates are known for their high caloric content, typically ranging from 307 to 354 kcal per 100 grams, and are a rich source of bioactive compounds (Baliga et al., 2011; Bentrad & Hamida-Ferhat, 2020; Rybicka et al., 2021). Table 2 presents the typical nutritional profile of date palm fruit, highlighting its macronutrient and micronutrient content. The concentration and composition of biocompounds may differ significantly, depending on the parameters, for instance, the cultivar, stage of ripeness, geographical origin, and environmental growing conditions (Eid et al., 2013; Sawaya et al., 1983). Dates are a rich source of energy, primarily due to their naturally occurring sugars such as glucose, fructose, and sucrose. Dates provide moderate amounts of dietary fibre, essential minerals (potassium, magnesium, calcium, and iron), and small quantities of protein and fat. They also contain antioxidants, particularly phenolics and flavonoids, which contribute to their antioxidant capacity. This nutritional richness makes dates a valuable component in both traditional diets and modern functional food formulations.

Table 2. Nutrient/ bioactive composition of date palm fruit.

Compounds	Composition	Reference
Carbohydrates	Make up approximately 73% of the fruit's dry weight, with glucose accounting for nearly 90% of the total sugar content, alongside notable amounts of fructose and sucrose.	(Maqsood et al., 2020)
Dietary fibres	It is estimated to range between 6.4% and 11.5% of the fruit's dry weight, comprising components, for instance, pectin, hemicellulose, lignin, resistant starch, and soluble fibres. A typical serving of 100 grams, equivalent to roughly seven to nine dates, can provide 25 to 30 grams of fibre, which meets the full daily recommended intake according to current U.S. dietary guidelines.	(Al-shahib & Marshall, 2003; Barber et al., 2020)
Protein	Roughly 3% protein and are notable for providing 23 distinct amino acids, many of which are rarely found in other commonly consumed fruits.	(Maqsood et al., 2020)
Oil (saturated and unsaturated fatty acids)	The oil content in date palm fruit varies significantly between its components. The edible flesh contains a relatively low amount of oil, ranging from 0.2% to 0.5%, whereas the seeds are much richer in lipids, comprising approximately 7.7% to 9.7% of their weight. Date seeds are known to contain up to 14 different fatty acids, although only eight of these are present in trace amounts within the fruit pulp. Among the unsaturated fatty acids found in the seeds are palmitoleic, oleic, linoleic, and linolenic acids. Notably, oleic acid constitutes a substantial portion of the seed oil, with concentrations ranging from 41.1% to 58.8%, indicating that date seeds have the potential to be a rich natural source of oleic acid.	(Al-shahib & Marshall, 2003)
Sterols	Sterol analysis of date fruits has identified a range of compounds, including cholesterol, campesterol, stigmasterol, β -sitosterol, and isofucosterol.	(Kikuchi & Miki, 1978)
Minerals	<ul style="list-style-type: none"> - Date palm fruits contain essential minerals, with around 15 different elements identified in their composition. The concentration of these minerals in dried dates can vary widely, ranging from as low as 0.1 mg, depending on the specific mineral and the variety of the date. - Potassium is particularly abundant, reaching up to 0.9% in the fruit pulp and approximately 0.5% in the seeds, making dates a valuable source of this vital electrolyte. - Other essential minerals found in dates are boron, calcium, cobalt, copper, fluorine, iron, magnesium, manganese, phosphorus, sodium, and zinc, all of which contribute to various physiological functions. - Date seeds also contain trace elements such as aluminium, cadmium, chloride, lead, and sulphur in varying concentrations, which may reflect environmental exposure and soil composition. - Fluorine, present in elemental form, is known for its role in dental health, particularly in preventing tooth decay. - Selenium, a trace element with antioxidant properties and a role in immune function and cancer prevention, has also been detected in dates. 	(Al-shahib & Marshall, 2003)
Vitamins	- Offer a variety of essential vitamins, which are vitamin C, thiamine (B ₁), riboflavin (B ₂), niacin (nicotinic acid), and vitamin A.	(Al-shahib & Marshall, 2003)
Carotenoids	<ul style="list-style-type: none"> - Research has identified the presence of carotenoids like lutein, β-carotene, and neoxanthin in date fruits. - In Algerian varieties like Deglet Noor, Tantebouchte, and Hamraya, β-carotene concentrations were measured at 6.4, 3.3, and 2.5 μg/100 g, respectively, while lutein levels were measured at 156, 28, and 33.6 μg/100 g. - Fresh and sun-dried varieties such as Fard, Khasab, and Khalas revealed that carotenoid degradation happened during the drying process, indicating a loss of these valuable compounds with post-harvest handling. 	(Al-Farsi et al., 2005; Al-Farsi & Lee, 2008; Boudries et al., 2007)

Table 2. Cont.

Phenolic compounds/ phenolic acids	<ul style="list-style-type: none"> - Amari date fruits possess higher levels of phenolic compounds compared to Hallawi dates at the same ripening stage. Specifically, Amari dates contain approximately 4.27 $\mu\text{mol GAE/g}$ of phenolic acids and 1.37 $\mu\text{mol GAE/g}$ of flavonols, whereas Hallawi dates exhibit lower concentrations, 0.38 $\mu\text{mol GAE/g}$ for phenolic acids and 0.43 $\mu\text{mol GAE/g}$ for flavonols. - The total phenolic content in various Iraqi date varieties ranges from 331 to 475 mg GAE/100 g, which is notably higher than the levels typically found in fruits such as apples, blueberries, oranges, pomegranates, papayas, bananas, and red grapes. - Tunisian date cultivars have been identified with several phenolic acids, including protocatechuic acid, vanillic acid, gallic acid, syringic acid, and p-coumaric acid, across three different varieties. - The concentration of phenolic acids of various Mauritanian date palms is significantly greater during the Khalal stage of ripening (0.729 g/100 g) compared to the Tamer stage (0.559 g/100 g). - Date seeds are nutritionally dense, containing approximately 3942 mg/100 g of phenolic compounds, and an impressive 80,400 $\mu\text{mol/100 g}$ of antioxidant capacity. 	<p>(Al-Farsi & Lee, 2008; Borochoy-Neori et al., 2015; Matloob & Balakita, 2016; Mohamed Lemine et al., 2014; Mrabet et al., 2016)</p>
Flavonoids	<ul style="list-style-type: none"> - At the Khalal stage of ripening, the Ajwa date cultivar has been observed to contain notably higher levels of the anthocyanidin petunidin (approximately 31 mg/100 g) compared to the Barni and Khalas cultivars at the same maturity stage. - In Deglet Noor dates harvested during the Khalal stage, researchers identified a diverse profile of flavonoid glycosides originating from apigenin, luteolin, and quercetin, including 19 isomeric variants, along with the presence of flavonoid sulfates. - In Oman, the total flavonoid and phenolic contents were assessed in three prominent date varieties, Fardh, Khasab, and Khalas, at two edible stages: Rutab and Tamr. The total phenolic content ranged from 81–178 mg GAE/100 g at the Rutab stage and 194–234 mg GAE/100 g at the Tamr stage. Correspondingly, the total flavonoid content varies from 19–66 mg CEQ/100 g and 25–34 mg CEQ/100 g, respectively. - 11 Saudi date varieties were identified to contain several flavonoids, including apigenin, luteolin, quercetin, isoquercitrin, and rutin. - Research on four Tunisian date cultivars demonstrated a decline in flavonoid content as the fruit matured from the Khalal to the Tamer stage. 	<p>(Amira et al., 2012; Eid et al., 2013; Hamad et al., 2015; Hong et al., 2006; Singh et al., 2012)</p>
Anthocyanins	<ul style="list-style-type: none"> - Only detected in fresh dates and may degrade or be lost during sun-drying processes. - Studies showed that Khasab exhibited the highest concentration of anthocyanins at approximately 1.5 mg/100 g, followed by Fard with 0.9 mg/100 g, and Khalas with 0.87 mg/100 g. - A strong correlation has been observed between the concentration of anthocyanins and the intensity of fruit colouration. 	<p>(Al-Farsi et al., 2005)</p>

Note: Units are presented as originally reported in the respective studies (mg/100 g, $\mu\text{g/100 g}$, $\mu\text{mol/100 g}$, mg GAE/100 g, mg CEQ/100 g, $\mu\text{mol GAE/g}$) to preserve data accuracy and reflect differences in analytical methods. Due to variations in testing protocols and reporting standards, converting all values to a single unit may introduce rounding errors or misrepresent the precision of the original data.

As demonstrated in Table 2, date fruits are recognised for their abundance of bioactive constituents with potential nutraceutical properties and contribute positively to human well-being. These biocompounds have been associated with a wide range of health-promoting effects, such as antioxidant, antimicrobial, antimutagenic, antihyperlipidemic, and anti-inflammatory activities. Beyond their distinct taste and texture, dates are also valued for their therapeutic potential, with

studies linking their consumption to a lower risk of chronic diseases, including cardiovascular disorders, certain cancers, and other health conditions (Bentrad & Hamida-Ferhat, 2020), as demonstrated in Table 3.

Table 3. Potential health benefits of date fruit.

Bioactive compounds	Health benefits	References
Carbohydrates	A 28-day intake of date seed and date flesh in powder form showed notable effects on blood biomarkers. Xylose (72.2%) and galactose (41.6%) were the main monosaccharides. Date seed powder showed stronger antibacterial activity and promoted cell growth effectively. Clinical results showed that date seed powder lowered C-reactive protein and triglycerides, and increased red blood cell counts.	(Noorbakhsh & Rabbani Khorasgani, 2023)
	In a mouse model, Deglet Noor date polysaccharides (DP) promoted the growth of beneficial bacteria like <i>Lachnospiraceae_NK4A136</i> and <i>Ruminococcaceae</i> . DP showed strong prebiotic effects and improved gut health by enhancing mucin-2 production and increasing tight junction protein expression, which strengthened the intestinal barrier. DP also reduced inflammation by lowering levels of cytokines IL-6, IL-17, and TNF- α .	(Ullah et al., 2024)
	Eating Algerian date varieties was found to have low glycemic indexes, reduced hunger and increased satiety. Algerian date varieties may be useful as functional foods that help with blood sugar control, appetite regulation, and cardiovascular health.	(Freha et al., 2016)
	A type of glucan extracted from Libyan date fruits was found to contain (1 \rightarrow 3)- β -D-glucan linkages, which are known for antitumor or anticancer properties.	(Ishurd & Kennedy, 2005)
	Date seed polysaccharides are comprised of monosaccharides, including galacturonic acid, glucose, mannose, fructose, and galactose. They demonstrated strong antioxidant and antimicrobial activities, especially against food-borne pathogens. They inhibited enzymes linked to diabetes and high blood pressure (α -glucosidase, α -amylase, ACE) They also showed cytotoxic effects against Caco-2 and MCF-7 cancer cells.	(Jayasree Subhash et al., 2024)
	Date seed protein hydrolysates had strong antioxidant, anti-inflammatory, and health-promoting properties. They inhibited lipid oxidation by 30%, β -carotene oxidation by 75% and low-density lipoprotein-cholesterol (LDL) oxidation by 60%.	(Ambigaipalan & Shahidi, 2015)
Date seed protein hydrolysates exhibited strong antioxidant activity and blocked free radicals effectively. DPPH: 72.5% ABTS: 92.5% OH: 64.5% NO: 57.9% They also showed good reducing power, and chelated metal ions (Fe ²⁺ : 73.2%, Cu ²⁺ : 40.1%), preventing oxidative damage.		

Table 3. Cont.

Fatty acids and derivatives	<p>Date seed oil reduced lipid peroxidation and preserved key antioxidant enzymes, such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx)</p> <p>It also helped to protect melanocytes from oxidative injury</p> <p>Date seed oil could be a promising treatment for skin conditions like vitiligo and melanoma.</p>	(Dammak et al., 2009; Ines et al., 2010)
	<p>Date palm seed oil from the “Barhi” cultivar contained mostly saturated fatty acids (50.24%), especially lauric, palmitic, and myristic acids.</p> <p>It also had monounsaturated fatty acids (40.33%), mainly oleic acid, and a small amount of polyunsaturated fatty acids (8.73%).</p> <p>The oil showed strong antioxidant activity and antimicrobial effects against several pathogens, especially <i>Staphylococcus aureus</i>.</p> <p>It also inhibited α-glucosidase activity, indicating potential anti-diabetic properties.</p>	(Hammami et al., 2025)
	<p>4 date palm cultivars (Mabroom, Safawi, Ajwa, and Mariami) were evaluated for their total phenolic content (TPC), antioxidant activity, and total anthocyanin content (TAC).</p> <p>Mariami had the highest TAC, while Mabroom had the lowest.</p> <p>Their antibacterial activity varied, with only Ajwa’s methanol extract showing effectiveness against all four tested bacteria: <i>Staphylococcus aureus</i>, <i>Bacillus cereus</i>, <i>Serratia marcescens</i>, and <i>Escherichia coli</i>.</p>	(Samad et al., 2016)
Phenolics compounds	<p>Flavonoid glycosides from date fruits cultivated in Al Madinah, Saudi Arabia, showed strong antimicrobial activity against imipenem-resistant <i>Pseudomonas aeruginosa</i>.</p>	(Selim et al., 2012)
	<p>Polyphenol-rich fraction from date fruit promoted the growth of beneficial bacteria, particularly bifidobacteria.</p> <p>It slowed down the growth of Caco-2 colon cancer cells after 48 hours, suggesting it may help prevent colon cancer.</p>	(Eid et al., 2014)
	<p>Date seed extract (DSE), a polyphenol-rich compound, showed strong antioxidant and therapeutic properties.</p> <p>DSE can block iron-related oxidative damage to DNA and proteins and reduce the activity of enzymes linked to neurodegenerative and pigmentation disorders, such as acetylcholinesterase and tyrosinase.</p> <p>DSE also exhibited dose-dependent anticancer effects by reducing the proliferation of liver, colon, and breast cancer cells through apoptosis.</p> <p>Gene expression analysis revealed that DSE downregulated anti-apoptotic markers (BCL-2 and P21) and upregulated the tumour suppressor gene P53, outperforming even the chemotherapy drug 5-FU in some cases.</p>	(Habib et al., 2022)
<p>Palm fruit pollen extract (PFPE), that are rich in polyphenols, demonstrated strong antioxidant and antimicrobial activities.</p> <p>It inhibited key enzymes such as acetylcholinesterase, tyrosinase, and α-amylase.</p> <p>In cancer cell studies, it suppressed the growth of colon (Caco-2), liver (HepG-2), and breast (MDA) cancer cells in a dose-dependent manner, causing cell death and stopping cell division.</p>	(Habib et al., 2023)	

One of the interesting facts about date palm fruits is that they offer several benefits for women’s health, including potential improvements in fertility, sexual function, and during pregnancy. Jahromi et al. (2022) investigated the impact of date palm supplementation on sexual function in infertile couples. The findings revealed that women in the intervention group showed an improvement in overall sexual function scores. Specific domains such as arousal, orgasm, lubrication, pain, and satisfaction also improved significantly compared to the control group. Similarly, men in the intervention group experienced notable enhancements in erectile function, sexual desire, orgasm, and overall satisfaction. These findings suggest that one-month supplementation with date palm may positively influence sexual function in infertile couples. Date palm pollen may also enhance certain aspects of female sexual function, particularly in areas such as desire, arousal, lubrication, and overall sexual performance (Jamali et al., 2025). During the pregnancy period, consuming date fruits offers several scientifically supported benefits for both the mother and the baby. Research by Yuliana et al. (2024) indicates that date palm juice can positively influence haemoglobin levels in pregnant women, making it a promising natural supplement for managing anaemia

during pregnancy. In terms of labour, the consumption of date fruits appears to positively influence labour outcomes by shortening gestation duration and the first stage of labour, while also promoting greater cervical dilation upon hospital admission, supporting a smoother and potentially faster childbirth process (Nasiri et al., 2019). There were findings that indicated that consuming date palm sap may help shorten the active phase of labour, thereby reducing the duration of pain and anxiety experienced by the mother during childbirth (Rahmani et al., 2023). Lastly, date palm fruit consumption positively influences postpartum recovery. The presence of natural oxytocin-like compounds in dates may support uterine contractions and enhance the involution process (Saragih et al., 2020).

In short, date palm fruits comprise diverse nutritional compounds that provide nutrient support and protection against various diseases and cancers, as well as for women, particularly infertility, pregnancy, delivery, and postpartum recovery. The bioactive compounds possess antidiabetic, antimicrobial, anti-inflammatory, and anticancer effects, making them suitable for daily consumption, even for diabetes patients. However, beyond its nutritional value, a more integrative analysis reveals its potential in functional food development, bioactive compound extraction, and biorefinery applications. Comparative studies show that different date varieties vary significantly in the composition, such as sugar, antioxidant, and fibre, which can influence their suitability for specific uses. Future research should investigate the variability in the biochemical composition of different date varieties, with a focus on how these differences influence their nutritional and therapeutic properties. Comparative studies across cultivars, growing conditions, and ripening stages could provide deeper insights into the bioactive compounds present.

4.2. Seeds

In date processing industries, the seeds are often considered a by-product or waste material that are largely underutilized, with common practices involving their disposal or limited use, for example, utilized in the Arab world to prepare a naturally caffeine-free beverage (Kiesler et al., 2024) or as components in animal feed. In recent years, powdered date seeds have gained popularity as a coffee alternative, offering a similar flavor profile without the stimulating effects of caffeine (Kiesler et al., 2024). Additionally, date seeds are commonly incorporated into livestock feed, with no reported adverse effects on animal health. Date seeds with a rich chemical profile support a wide range of multifaceted applications.

Date seed oil is distinguished by its relatively high extraction yield, typically ranging from 5% to 13%. Its fatty acid profile includes both saturated and unsaturated types, with lauric and oleic acids being the most prominent. In addition to its lipid composition, the oil is enriched with health-promoting bioactive constituents such as tocopherols, tocotrienols, phytosterols, and phenolic compounds. These components contribute to its potential value across various industries, including food formulation, cosmetics, and pharmaceuticals. One notable advantage of date seed oil is its distinct dark yellow coloration, which sets it apart from conventional vegetable oils. Additionally, it exhibits a relatively high oxidative stability, allowing for extended shelf life under appropriate storage conditions (Mrabet et al., 2020). Due to high thermal stability, date seed oil is ideal for culinary applications such as cooking, frying, and seasoning, and even as a potential replacement for palm olein (Nehdi et al., 2018). The natural carotenoid content has a yellowish hue, making it ideal for margarine production without the need for synthetic colorants (Nehdi et al., 2010). The study by Basuny and Al-Marzooq (2011) demonstrated the successful substitution of conventional corn oil with date seed oil in mayonnaise formulations, resulting in improved sensory attributes.

The presence of oleic acid in date seed enhances its functionality in topical applications, as this fatty acid is known to improve skin permeability, an important feature in the delivery of active ingredients in skincare products (Mrabet et al., 2020). Studies have shown its effectiveness in reducing oxidative stress and cellular and DNA damage in skin cells due to UV-A and UV-B radiation (Besbes et al., 2004). Ines et al. (2010) investigated the chemopreventive potential of date seed oil using human epidermal keratinocyte models and found that it effectively mitigated oxidative stress induced by hydrogen peroxide, without exhibiting cytotoxicity at concentrations up to 30 µg/mL. In a related study, they observed that skin samples treated with date seed oil showed significantly reduced DNA damage, approximately four times lower, following UV-B exposure, compared to untreated samples (Dammak et al., 2010). The underlying cause of these protective responses has been linked to the oil's high levels of phenolic compounds and tocopherols, reinforcing its potential as a natural photoprotective agent (Dammak et al., 2010; Ines et al., 2010). The date seed oil has also been used to synthesize natural cosmetic creams, offering performance comparable to commercial products, with the added benefit of replacing synthetic ingredients with natural alternatives (Lecheb & Benamara, 2015). Date seed has also been incorporated as a component in eye-shadow formulations within the cosmetics industry (Benchelah & Maka, 2006). Date seed oil, which contains phytosterols, essential fatty acids, and other nutrients, has also been shown to promote scalp health, stimulate hair growth, and support the function of sebaceous glands and hair

follicles (Walke & Daud, 2018). Unlike synthetic skincare products that often contain parabens that are known to cause allergic reactions in sensitive skin, date seed oil offers a natural alternative with reduced risk of irritation (Alharbi et al., 2021). Beyond skincare, the oil has shown protective effects on human sperm under oxidative stress, which revealed that the oil enhanced both sperm motility and viability, particularly after 24 hours of incubation (Fatma et al., 2009). These findings highlight date seed oil shows potential as a natural component for nutricosmetics applications.

Interestingly, low free fatty acids of date seed oil are emerging as a versatile resource for biodiesel production, as demonstrated by Azeem et al. (2016). Biodiesel produced from date seed oil extracted from Zahidi, Basra, and Khazravi varieties met key fuel standards (EN14214 and ASTM D6751), showing favorable properties such as high cetane numbers (55–60.3), low iodine values (44–50), and suitable flash points (135–140 °C; Azeem et al., 2016). On the other hand, Al-Zuhair et al. (2017) conducted comparative studies using NaOH and Novozym®435 catalysts, which showed similar yields, though NaOH exhibited greater selectivity for specific fatty acids. Additionally, date seed oil has been evaluated as a feedstock for producing poly(3-hydroxybutyrate) (PHB), a biodegradable polymer (Yousuf & Winterburn, 2017). *Cupriavidus necator* was able to utilize the date seed oil as a sole carbon source via fermentation, yielding PHB with properties comparable to conventional formulations. In short, date palm seeds, often considered agricultural waste, are increasingly recognized for their potential in sustainable applications. For example, oils derived from agricultural waste, such as date seeds, are generally more cost-effective than refined edible oils in the production of bioproducts, such as the replacement of synthetic ingredients, skincare products, and biopolymers. Despite these promising avenues, critical reflection highlights limited scalability in commercial valorization, so future research should focus on integrated seed valorization strategies to convert seed biomass into multiple high-value products, thereby reducing waste and enhancing resource efficiency across the date palm value chain.

5. Date Palm as a Bioremediation Agent

Air quality is typically assessed using instrumental monitoring systems, such as bulk and wet deposition samplers, which are commonly employed to measure atmospheric pollutants. However, an alternative and increasingly recognised approach is biomonitoring, which involves evaluating the accumulation of contaminants in living organisms. This method provides valuable insights into the biological impact of air pollution and complements traditional monitoring techniques by offering a more integrated view of environmental exposure (Guéguen et al., 2011).

Using plants as natural indicators to monitor trace element deposition is becoming a widely accepted approach in environmental science. Their ability to absorb and retain pollutants, combined with their broad distribution, makes them ideal for collecting extensive environmental data. This technique is particularly useful for tracking airborne metal contaminants in urban areas. Vegetation-based monitoring is favoured for its low cost and ease of implementation, offering a practical alternative to more expensive and labour-intensive direct sampling methods. It enables researchers to examine large-scale patterns and changes over time in heavy metal pollution with minimal resources. As a result, this method provides an efficient and scalable solution for assessing environmental contamination (Bu-Olayan & Thomas, 2002). Date palm trees have been utilised in various environmental studies across multiple countries as biological indicators for assessing the distribution of heavy metals. Their natural ability to absorb and accumulate trace elements from the atmosphere and soil makes them effective tools for monitoring pollution levels. This approach has proven valuable in mapping contamination patterns and evaluating environmental health in regions where date palms are commonly cultivated, as demonstrated in Table 4.

Table 4. Role of date palm in evaluating environmental quality and exposure to pollutants.

Location	Date palm components	Findings	Reference
Aqaba, Jordan	Leaves	The highest levels of heavy metals were found in areas with heavy traffic, showing a clear link between urban activity and metal pollution. In contrast, rural and control sites had much lower levels, suggesting less contamination in those areas.	(Al-Khlaifat & Al-Khashman, 2007)
Riyadh city, Saudi Arabia	Leaves	The concentrations of metals such as lead (Pb), zinc (Zn), copper (Cu), nickel (Ni), chromium (Cr), and lithium (Li) were analysed in both washed and unwashed leaflets from different locations (urban, suburban, highway, industrial, and rural (control) sites). The results showed that more metal contamination, especially Pb and Zn, was found on the surface of unwashed leaves, pointing to air pollution as the main source. This showed that date palm leaflets can be useful tools for monitoring heavy metal pollution, especially in dry regions.	(Al-Shayeb et al., 1995)
Ahvaz city, Iran	Palm leaves and mesh fibers	The amount of potentially toxic elements (PTEs) was higher in places with more industrial activity and traffic, and lower in areas farther from roads and factories. When comparing plant parts, date palm mesh fibers accumulated more PTEs than leaflets. This was likely because the fibers have thicker layers, a rough surface, and grow longer, making them better at trapping airborne pollutants.	(Jafari et al., 2023)
	Leaves	Date palm leaves exhibited an average isothermal remanent magnetization (SIRM) value of 120% higher than that of buttonwood (<i>Conocarpus erectus</i>), showing they are better at trapping magnetic particles. Mapping these magnetic properties showed a strong link between particulate matter (PM) and traffic-heavy areas, especially near main roads and service zones. Their strong performance as long-term pollution monitors is due to their tough structure, including multi-layered mesh fibers, a rough surface, and a long lifespan, which enhances their ability to trap and retain airborne pollutants over time.	(Almutawa & Roeland, 2022)
Kuwait	Leaves, bark, fruit, and surface soil	Lead levels were measured in various parts of the date palm, including washed and unwashed leaves, bark, fruit, and surface soil. Statistical analysis using ANOVA revealed a significant difference between washed and unwashed leaf samples, indicating that a substantial portion of lead contamination is surface-bound. Since only 20% of the lead was removed by washing, about 80% was absorbed into the leaf tissue. Lead levels were highest near industrial areas, followed by highways, and then urban zones. Among the plant parts, unwashed leaves had the most lead (5.06 µg/g), followed by washed leaves (3.52 µg/g), fruit (2.88 µg/g), and bark (1.47 µg/g). Soil samples had the highest overall lead concentration (6.86 µg/g), showing that local pollution sources strongly affect lead levels in the environment.	(Bu-Olayan & Thomas, 2002)

In addition to its role as a biomonitoring agent, the date palm also shows promise as a bioremediation tool. Its natural ability to absorb and accumulate pollutants, particularly heavy metals, makes it a valuable resource for environmental cleanup efforts. The application of date palm as a bioremediation agent is a low-cost, sustainable, and eco-friendly approach to mitigate

environmental pollution. Large quantities of date palm biomass waste, including leaf, trunk fibre, and seed, are generated annually, yet much of it remains underutilised. It is estimated that a single date palm tree can produce up to 20 kg of organic waste per year (Awad et al., 2023; Faiad et al., 2022; Martis et al., 2020). The study by Awad et al. (2023) showed the potential of date palm trunk fibres (DPTF) as low-cost, renewable, and eco-friendly adsorbents for removing contaminants from water. Their robust structure and high surface area enable effective binding of heavy metals such as cadmium, making them suitable for use in sustainable wastewater treatment systems. DPTF demonstrated a notably high sorption capacity of cadmium from wastewater, reaching 51.5 mg/g at a low flow rate, which surpassed the performance of other commonly used biosorbents. Next, Basheer et al. (2021) synthesised nanostructured powder-activated carbon (nPAC) using date palm fibre as the precursor material to remove aluminium ions (Al^{3+}) from aqueous solutions. Under the optimised conditions, the nPAC demonstrated a removal rate of 99.5% and an adsorption capacity of 9.958 mg/g, which confirmed that date palm fibre-based activated carbon is a low-cost, environmentally sustainable, and effective material for the adsorption of Al^{3+} removal, offering a promising solution for eco-friendly wastewater treatment. Raw and chemically modified date palm fibre waste (RDPF and NaOH-CMDPF) were studied for their capability to remove phenol from water. Chemical treatment with NaOH significantly enhanced the adsorption capacity and achieved up to 86% phenol removal compared to untreated fibres (81%), concluding that date palm fibre waste is an affordable and green alternative for promoting sustainable water treatment and waste valorisation (Siva Kumar et al., 2023).

The development of a novel composite material (ZnO@DPS-AC) derived from date palm spikelets (DPS) was shown to be efficient for water purification, specifically targeting the removal of methyl orange (MO) dye. ZnO@DPS-AC exhibited rapid adsorption performance, removing more than 45% of MO within the first 10 minutes and achieving up to 99% removal under optimised conditions. The composite also proved effective in treating actual wastewater and removing various other contaminants, underscoring the value of converting agricultural waste into high-efficiency adsorbents (Al-Hazeef et al., 2024). Besides, Fseha et al. (2023) explored the use of biochar-based date palm fronds and leaves for the phenol adsorption from wastewater. Biochar from date palm fronds exhibited the highest removal efficiency, achieving 64% phenol reduction and an adsorption capacity of 15.93 mg/g. When used with treated synthetic wastewater, phenol removal rates of 60% and 85% were obtained, with respective adsorption capacities of 241 mg/g and 22.28 mg/g. Reusability experiments demonstrated sustained adsorption performance, reinforcing the potential of biochar-based date palm fronds as a low-cost and reusable adsorbent for phenol removal in wastewater treatment (Fseha et al., 2023). Date palm flower stalks (PFS) can serve as effective materials for treating wastewater, as demonstrated by Arroussi and Laksaci (2024). Untreated PFS was employed as a natural biosorbent for removing textile dyes. A maximum biosorption capacity of 38.522 mg/g was achieved under optimised conditions. The adsorption process was more efficient under alkaline conditions, with the point of zero charge determined to be 6.3 (Arroussi & Laksaci, 2024). Mahmoud et al. (2024) investigated the ability of biochar derived from date palm leaf midribs, produced via slow pyrolysis, for removing Pb (II) and iodine from water. The experiments showed complete removal of Pb (II) with 60 mg of biochar per 10 mL solution, while iodine removal peaked at 39.7% with 30–40 mg per 50 mL (Mahmoud et al., 2024).

Another investigation demonstrated the potential of date seeds in treating wastewater by eliminating dye pollutants. Din et al. (2024) investigated the use of oxidised activated carbon synthesised from date palm seeds (OACDS) as a sustainable material for dual environmental applications: wastewater treatment and soil moisture enhancement. OACDS can efficiently adsorb Rhodamine 6G dye, achieving up to 88.06% removal under optimal conditions. Regeneration studies revealed a 10.9% decline in adsorption capacity after five reuse cycles, suggesting good reusability and economic viability. OACDS also demonstrated promising water retention capabilities when incorporated into soil. Its application in clay and sandy soils improved moisture retention, with the clay-OACDS mixture reaching a peak retention of 16.8 mL. The material's porous and textured surface contributes to better water holding capacity, which may enhance crop productivity (Din et al., 2024). Date seed can also be used to produce biochar and shows strong potential for removing pesticides from wastewater (Mihajlović et al., 2025). Preliminary estimates suggest biochar produced from date seeds may serve as a viable alternative to commercial activated carbons, especially in decentralised or small-scale applications. Its high adsorption efficiency, capable of eliminating up to 92.6% of carbendazim and 89.4% of linuron, demonstrates its effectiveness against persistent pesticide pollutants. This capability also suggests broader applicability for removing other micropollutants such as phenols, pharmaceuticals, endocrine disruptors, microplastics, and heavy metals. Beyond water treatment, date seed-biochar also holds promise for carbon sequestration, soil improvement, and use in sustainable construction materials, contributing to multiple Sustainable Development Goals (SDGs), as illustrated in Figure 2 (Mihajlović et al., 2025).

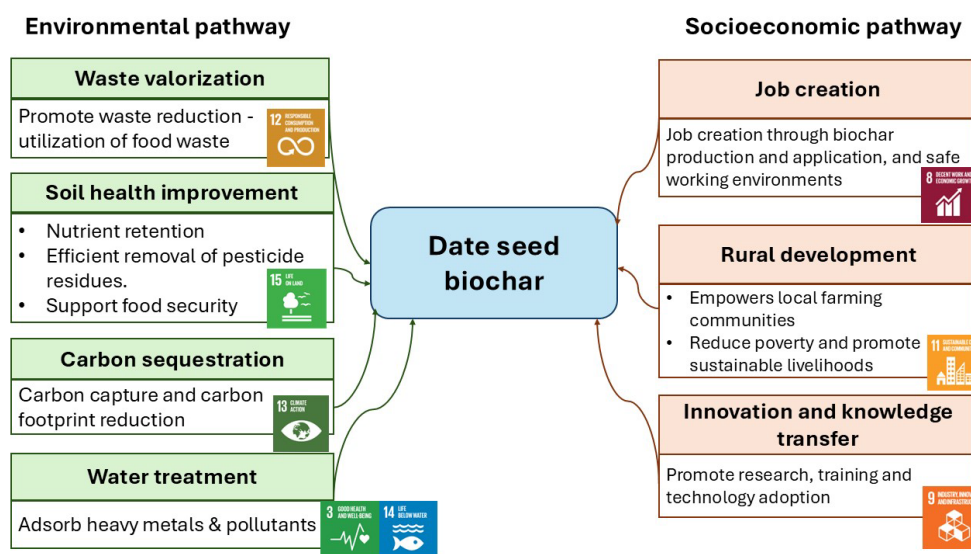


Figure 2. Transformative Pathways of Date Seed Biochar Toward Achieving SDGs. Adapted from Mihajlović et al. (2025).

To evaluate the effectiveness of date palm-derived materials in environmental bioremediation compared to conventional approaches, assessments such as comparative analysis and life cycle analysis have been conducted. Research indicates that date palm biomass can be transformed into biochar or used as an adsorbent, offering a cost-effective and sustainable alternative for pollutant removal. The study by Remmani et al. (2024) showed that biochar made from date palm seeds was efficient than commercial activated carbon in removing trichloroethylene and tetrachloroethylene from water, showing better performance. This high removal efficiency was due to the high surface area and nanotubular structure possessed by the biochar. Shaheen et al. (2022) compared date palm waste biochar with activated carbon produced from woody biomass in terms of environmental impact, cost, and adsorption performance. Using a life cycle assessment approach and Simapro 8.5 software, the results showed that date palm biochar had a lower carbon footprint, with global warming potentials (GWP) of 1.53 kg CO₂Eq/kg, as compared to activated carbon (8.96 kg CO₂Eq/kg). The cumulative energy demand (CED) for biochar was 20.3 MJ/kg, while activated carbon required 119.5 MJ/kg. The adsorption capacity was similar, but date palm biochar was cheaper with a production cost of \$1.06/kg compared to \$1.34/kg for activated carbon. In summary, the literature studies highlight the date palm tree as a multifunctional, eco-friendly material for environmental remediation.

6. Limitations and Future Work

Despite the growing body of literature on date palm, several research gaps remain that limit the translation of date palm into sustainable solutions. To address this, future research must be guided by research questions, supported by feasible experimental designs, and strengthened through interdisciplinary collaboration.

6.1. Research Questions

Based on the synthesis of current literature, the following research questions are proposed:

- (1) How can Artificial Intelligence systems be optimized for date palm plantations under arid conditions?
- (2) What are the effects of emerging postharvest and processing technologies on the physico-chemical properties of different date cultivars across various ripening stages?
- (3) Which extraction techniques yield the highest yield of bioactive compounds from date palm fruits and seeds, and how can these be scaled for industrial use?
- (4) How can date palm be effectively used as a biomonitor for environmental applications, and what protocols are needed for regular safety assessments?

6.2. Future Studies

Date palm fruits and seeds are increasingly recognised for their nutritional and therapeutic value, which contributes to the prevention and management of chronic diseases, including diabetes, cardiovascular conditions, and certain cancers. Recent research has focused on extracting bioactive

compounds from dates using advanced techniques to develop functional foods. However, understanding their health effects is complex due to variations in date composition, extraction methods, and digestive behavior. The following future research directions are proposed to address the identified gaps.

6.2.1. Cultivar-Specific Analysis and Ripening Dynamics

Future studies should be focused on the comprehensive analysis and characterization of different date cultivars across diverse geographic regions and ripening stages to unlock their full potential. Date palm fruits experience notable transformations in their physical and chemical attributes throughout the ripening process. These changes include variations in moisture levels, sugar content, and mechanical properties such as firmness and elasticity (Ghonimy et al., 2025). Analysing the physical and mechanical traits of various date palm cultivars throughout their ripening stages is vital for enhancing postharvest strategies, refining processing methods, and tailoring their use across different industrial applications (Hassan et al., 2025). Hassan et al. (2025) used Hertz Theory to estimate the toughness of Barhi, Saqie, and Khodry dates at different ripening stages (Khalal, Rutab, and Tamar). The findings revealed that as moisture content declined during ripening, fruit size and mass decreased, leading to denser tissue in the Tamar stage. Mechanical testing revealed a significant drop in elasticity and rupture stress from Khalal to Rutab, indicating softening, followed by a slight firmness increase at Tamar due to dehydration. Measured and predicted toughness values closely matched, with minimal deviation (0.00–9.24%), confirming the model's reliability for assessing textural changes during ripening.

6.2.2. Advanced Technologies for Precision Agriculture and Postharvest Management

Recent innovations, such as edible coatings, advanced drying methods, smart packaging, and AI-driven tools like deep learning and computer vision, have enabled precise, automated classification of fruit maturity. Accurate determination of ripening stages is essential for minimising postharvest losses and preserving quality across different date palm cultivars. These technologies support precision harvesting and enhance postharvest efficiency. Khan et al. (2024) introduced a novel machine learning framework to classify date bunch types and ripeness levels and identify healthy versus white-scale disease (WSD) stages in date palm leaflets. Enhanced deep learning models, particularly VGG16, achieved high accuracy across datasets, with up to 99.7% for disease classification. The use of XAI techniques provided valuable insights into model decisions, supporting more informed and sustainable agricultural practices. At the industrial level, King Abdullah University of Science and Technology (KAUST), Saudi Arabia, is developing a robotic system for automating key agricultural tasks such as harvesting, pollination, and tree maintenance in date farming. The system uses AI-powered robotic arms equipped with high-precision visual sensors to identify and handle individual dates with speed and accuracy, reducing labour risks and improving yield quality. Field trials are set for the 2025 harvest season, with full deployment expected within three years. This Robots-as-a-Service model is proposed to make the technology accessible to smaller farms (KAUST, 2025).

6.2.3. Advanced Processing Techniques

Processing methods significantly influence sugar profiles, texture, polyphenol retention, and sensory attributes (Al-Habsi, 2025). Traditional preservation methods like sun drying, smoking, and salting remain widely used but face limitations in scalability and quality retention, making them less suitable for commercial use. The emerging processing methods, including controlled atmosphere storage, irradiation, high-pressure processing, pulsed electric fields, and cold plasma, offer chemical-free alternatives to conventional methods and address key postharvest challenges such as microbial spoilage and texture degradation, reducing postharvest losses. A preservation method that works well for one cultivar may be ineffective for another, making universal postharvest protocols impractical. As a result, preservation processes often require cultivar-specific adjustments, which complicates standardization and poses challenges for scaling and innovation in the industry. In the future, hurdle technology, an emerging approach to postharvest date treatment that combines multiple physical, chemical, and biological methods, is proposed to enhance safety, extend shelf life, and maintain quality. Techniques such as high-pressure processing, pulsed electric fields, modified atmosphere packaging, cold plasma, and irradiation work synergistically to inhibit microbial growth, control respiration, and preserve texture and nutrients. The flexibility of hurdle technology allows for tailored preservation strategies based on the specific physicochemical properties of each variety, supporting sustainable, clean-label food systems and reducing environmental impact.

6.2.4. Smart Packaging

The integration of sensor-enabled smart packaging represents a transformative advancement in postharvest management of date palm products. These intelligent systems are capable of real-time monitoring of factors like freshness and humidity, which improves storage control and shelf life. AI technologies are increasingly used to forecast spoilage trends and customise preservation

strategies based on cultivar and environmental conditions (Mondol et al., 2025). For instance, machine learning models can analyse historical data on ripening behaviour, microbial growth, and packaging performance to predict optimal storage durations and identify early signs of degradation. These predictive capabilities are particularly valuable for managing the variability in physicochemical properties across different date palm cultivars and ripening stages. From a supply chain perspective, these technologies support precision logistics, enabling real-time tracking of product quality from farm to consumer. This not only improves inventory management and reduces waste but also facilitates compliance with food safety regulations and quality assurance standards. Critically, the adoption of smart packaging and AI tools must be accompanied by the standardization of sensor technologies to ensure compatibility across packaging formats and cultivars and cost-benefit analysis to evaluate economic feasibility, particularly for small and medium-scale enterprises.

6.2.5 Scalability of the Extraction Approach for Industrial Applications

Different extraction methods, such as ultrasound-assisted, enzyme-assisted, and supercritical fluid extraction, have been utilised to extract bioactive compounds from date palm fruits and seeds. While various extraction techniques for valorising date palm biomass have been previously reviewed and evaluated, future research should focus on their scalability for industrial applications. Scaling up these methods is essential to transition from lab-scale efficiency to commercial viability, especially in regions where date palm waste is abundant. Moreover, integrating multiple extraction approaches, such as combining mechanical, thermal, and biochemical methods, could enhance the recovery of valuable compounds and ensure comprehensive utilisation of the material. A synergistic strategy not only improves yield and purity but also supports circular economy principles by minimising waste and maximising resource recovery from date palm residues.

6.2.6. Safety of Date Palm as a Biomonitoring Agent

Date palm, especially leaves, has also shown its potential as a biomonitoring agent for environmental pollutants, particularly heavy metals. In the future, a quantitative analysis of the underlying adsorption mechanisms of date palm as a biomonitoring agent should be conducted. Recognising this limitation, adsorption isotherms such as Langmuir and Freundlich, along with kinetic models like pseudo-first-order and pseudo-second-order, can be applied to describe the physicochemical interactions between heavy metals and date palm tissues. These investigations will provide a more mechanistic understanding of heavy metal uptake and strengthen the scientific foundation for using date palm in environmental monitoring strategies. Variability in heavy metal uptake has also been observed across different date palm varieties. From a critical standpoint, the use of date palm as a biomonitoring agent presents both opportunities and challenges. On one hand, its widespread cultivation and adaptability make it a practical candidate for large-scale environmental surveillance. On the other hand, the lack of standardised protocols for sampling, analysis, and interpretation limits its current utility. Future research should focus on the development of standardised biomonitoring protocols using date palm components, including sampling frequency, component selection, and analytical methods. Mapping heavy metal accumulation across cultivars and regions, supported by geospatial tools and environmental data integration, is needed. The physiological mechanisms of heavy metal uptake and translocation within the date palm components for safer consumption are also needed for investigation. AI and sensor technologies can be integrated for real-time detection and predictive modelling of contamination risks in date palm farming systems. These efforts will not only enhance food safety and public health but also position date palm as a strategic resource in environmental monitoring management.

6.2.7. Policy and Collaboration

Future work should explore policy support approaches, such as incentive programs, digital infrastructure investments, standardization, and regulatory frameworks that promote technology adoption in arid agriculture. The government can introduce subsidies or grant schemes to encourage the adoption of precision agricultural tools in date palm farming. Establishment of cultivar-specific quality standards and safety protocols will facilitate the commercialisation of date-based bioproducts. Policies also need to consider the date palm as a biometric for heavy metals, ensuring regular testing and compliance with food safety thresholds. The complexity of challenges in date palm necessitates the interdisciplinary collaboration among academic institutions and industry to enhance knowledge exchange, community engagement, co-development of technologies, and pilot-testing in real-world settings. Cross-national collaborations are valuable for informative studies on different date cultivars' performance and technology transfer among the regions. Lastly, the involvement of local farmers in the use of digital and advanced tools ensures relevance and long-term sustainability.

7. Conclusion

In short, the versatility of the date palm has drawn significant attention lately, owing to its wide range of uses in multiple sectors across food, pharmaceutical, and nutraceutical domains. This review underscores the versatile utility of date palm fruits and their seeds, which are increasingly recognized as rich reservoirs of bioactive compounds. The sustainable utilization of every date palm component can be enhanced through circular bioeconomy principles. From fruit processing residues to fronds and seeds, each component of the date palm offers opportunities for value-added transformation, contributing to waste minimization and resource circularity. Numerous studies have documented the presence of essential nutrients, antioxidants, dietary fibers, and phytochemicals that support the health-promoting attributes. Beyond traditional consumption, the integration of date-derived ingredients into processed food products is gaining momentum in both research and commercial sectors. The health-promoting attributes of dates, for instance, their anti-inflammatory, antimicrobial, and antioxidant effects, make them ideal candidates for the formulation of functional foods aimed at improving public health outcomes. Moreover, the natural sweetness and nutrient density of dates support their use as healthier alternatives to refined sugars and synthetic additives. The growing consumer demand for clean-label and health-oriented products has further accelerated innovation in date-based food technologies. Importantly, recent studies have also identified the potential of date palm, particularly its fruits and leaves, as effective biomonitors for heavy metal contamination and air quality index. Due to their high bio-accumulation capacity, date palm components can serve as eco-friendly tools for assessing environmental pollution, especially in arid and semi-arid regions where industrial and agricultural activities pose contamination risks. By aligning its applications with sustainable development goals, particularly those related to food security, bioremediation, and responsible consumption, the date palm can serve as a model for integrated bio-refinery systems in arid regions. Future research and policy frameworks should prioritize scalable technologies that reinforce the ecological and economic resilience of date palm cultivation and utilization.

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Abbreviations

The following abbreviations are used in this manuscript:

CSIS	Automated subsurface irrigation system
S-BIS	Sensor-based method
T-BIS	Time-based scheduling
DI	Drip irrigation
SI	Subsurface irrigation
ET _c	Evapotranspiration
IoT	Internet of Things
GAE	Gallic acid equivalents
CEQ	mg catechin equivalents
DP	Deglet Noor date polysaccharides
LDL	Low-density lipoprotein-cholesterol
SOD	Superoxide dismutase
CAT	Catalase
GPx	Glutathione peroxidase
TPC	Total phenolic content
TAC	Total anthocyanin content

DSE	Date seed extract
PEPE	Palm fruit pollen extract
PHB	Poly(3-hydroxybutyrate)
PTEs	Potentially toxic elements
SIRM	Saturation isothermal remanent magnetization
PM	Particulate matter
DPTF	Date palm trunk fibres
nPAC	Nanostructured powder-activated carbon
MO	Methyl orange
DPS	Date palm spikelets
PFS	Date palm flower stalks
OACDS	Oxidised activated carbon synthesised from date palm seeds
SDGs	Sustainable Development Goals
GWP	Global warming potentials
CED	Cumulative energy demand
WSD	White-scale disease
AI	Artificial intelligence

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