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Current insights into date by-product valorization for sustainable food industries and technology

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The date palm holds immense significance in the socio-economic fabric of the countries where it is extensively cultivated. The plant and its derivatives boast diverse nutritional and functional properties, contributing to a substantial global production surge. Despite various initiatives to convert date processing waste into value-added products, a significant proportion of waste persists in the form of date seeds, date pomace, and lost dates. The physicochemical and nutritional profiling of date seeds and pomace reveals functionalities that, if properly utilized, could transform them into economically viable, natural, and sustainable ingredients across various sectors. Although ample literature exists on date palms and their industrially relevant waste products, this review distinctly focuses on date seed and pomace as pivotal by-products of date processing. The objective is to furnish comprehensive and updated insights into the valorization of date seeds and pomace, emphasizing their applications in the food industry. This review also endeavors to illuminate approaches for minimizing the wastage of these industrial by-products and highlights the bioactive components inherent in them.

Sustainability spotlight

The manuscript provides a comprehensive exploration of sustainable practices in the food industry by focusing on the valorization of date by-products, specifically seeds and pomace. By addressing the physicochemical and nutritional profiling of these by-products, the review sheds light on their potential as economically viable, natural, and eco-friendly ingredients. The manuscript emphasizes strategies for minimizing waste, promoting sustainable utilization, and highlights bioactive components with potential health benefits. Through this work, we contribute valuable insights into sustainable technologies for food ingredients, processes, and packaging.

1. Introduction

Fruits have gained prominence in dietary choices due to their rich biocomponents, including carbohydrates, minerals, vitamins, and fibers. The World Health Organization (WHO) recommends daily fruit intake for their bioactive, nutraceutical, and health benefits,[1,2] promoting overall health and well-being. A wealth of evidence links fruit and vegetable consumption to a reduced mortality rate from various diseases, including tumors.[3] This success is attributed to the inherent bioactive compounds, dietary fiber, and antioxidants present in fruits and vegetables.[1,4] In the Middle East and North Africa region (MENA), date fruits derived from the common date palm tree stand out as one of the most common functional and nutrient-packed fruits. Scientific evaluations have identified biomacromolecules in date fruits that contribute to human health, addressing infectious and degenerative diseases such as cancer, gastric disorders, and hypercholesterolemia.[5]

The date palm (*Phoenix dactylifera* L.), a dioecious monocotyledonous tree belonging to the family Arecaceae and the subfamily Coryphoideae, encompasses approximately 200 genera and over 2500 species.[6] Cultivated since ancient times, date palms have played pivotal roles in medicine, socioeconomics, ornamentation, environmental sustainability, and nutrition.[7–9] Although historical records provide limited information on the origin of date palms, ancient Mesopotamia (now Southern Iraq) and the Nile Valley in Egypt are recognized as their sources. Domestication occurred from the Neolithic period through the Bronze Age, as evidenced by carbonized seed materials.[10–13] Date palms originated in the Near East region in Mesopotamia around 4000 BC before becoming integral to the social and economic lives of arid and semi-arid regions, thriving in hot climates with minimal rainfall and low humidity.[14] Geographically, Arabian countries and Iran are global leaders in date palm cultivation, accounting for about 70% of the global production.[15–18] However, date palms have also spread to tropical, subtropical, temperate, and arid regions globally, including South America, South Africa, Southern Spain, West

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Asia, the Mediterranean coast of Africa, Pakistan, Mexico, Australia, India, and parts of the United States (California, Texas, and Arizona).[6,19] With over 2000 global cultivars named according to their originating country,[19,20] date palms offer more than just fruits. They provide ligneous midribs, stalks, and fibers from leaves and fronds used in manufacturing building materials, fuel, basketry, and packaging materials.[21,22]

Fig. 1 illustrates some of the global importance of cultivating date palms. Beyond the cultural and spiritual significance, especially in MENA, central and South Iraq, Upper Egypt, and Northern Sudan, date cultivation profoundly influences the economies of producing countries. The MENA region, characterized by hot and dry climates, remains a major producer, accounting for 67% of total date exports and 75% of global date production, with India being the top consumer of date fruits.[5,23–26] In 2020, global date palm cultivation covered about 1.3 million hectares, producing approximately 9.5 million tons of date fruits.[25] Asia reported the largest cultivated area at 62.43%, followed by Africa at 36.72%, while America and Europe each accounted for less than 1%. FAO statistics identified Egypt, Saudi Arabia, Iran, Algeria, the United Arab Emirates, Pakistan, and Sudan as the top seven date-producing countries.[25] Recent trends indicate a steady increase in date palm production, attributed to documented nutritional and health values, along with innovations in cultivation and processing, leading to the introduction of new date-derived products.[10] The global date fruit market is expected to witness significant growth between 2022 and 2030, driven by strategic initiatives by key producers.[25]

Date fruits are the cornerstone of date palm products from an economic perspective, being consumed as fresh or dried whole fruits or processed into various food products, such as jams, syrups, sugars, jellies, juice, and pastes.[7,24,27] Physiologically, the date fruit is a one-seeded drupe enclosed in a fleshy

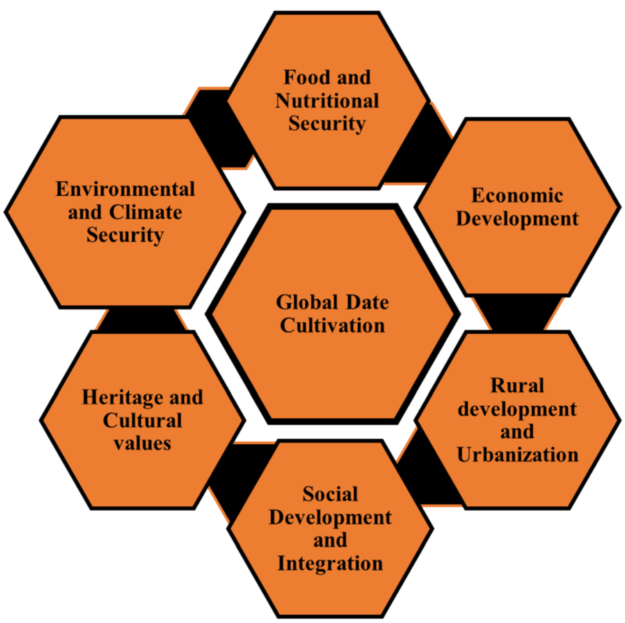

Fig. 1 Importance of global date cultivation.

Table 1 Characteristics of date fruits at developmental stages

S/N	Stage name	Maturity	Growth period (weeks)	Color	Texture	Taste	Moisture content (%)	Sugar content (%)	Edibility	Reference
1	Hababouk	Young immature	4–5	White	Fluffy	—	80–90	—	No	Fernández-López *et al.* (2022),[10] Hussain *et al.* (2020)[32]
2	Kimri	Immature	9–14	Green	Turgid	Bitter	75–85	20	No	Krueger (2021),[229] Martín-Sánchez *et al.* (2014)[34]
3	Khalal	Mature	6	Yellow, pink, red, purple	Turgid	Slightly bitter	40–60	50	Yes	Golshan and Fooladi (2006),[230] Martín-Sánchez *et al.* (2014)[34]
4	Rutab	Mature	2–4	Yellow, brown, black	Soft	Sweet	30	72–88	Yes	Baliga *et al.* (2011),[15] Krueger (2021)[229]
5	Tamar (ripe and dried)	Mature		Black or brown	Hard	Sweet	20–25	72–88	Yes	Al Udhaib (2015),[231] Krueger (2021)[229]

pulp of pericarp, mesocarp, and endocarp,[24] holding pivotal significance, particularly in MENA regions.[1,28,29] In many Arabian and Islamic countries, date fruits serve as traditional snacks during hospitality events, often accompanied by dairy products and coffee, especially in Gulf countries.[20] Moreover, the social and economic value of oasis residents in MENA countries is intertwined with date palms and fruits owing to their inherent nutritional, medicinal, environmental, and structural applications.[20] Despite the global variety in date cultivars, characterized by differences in size, color, taste, and ripeness degree, they all undergo a maturation cycle encompassing five stages over seven months, with each stage named according to the originating country.[15,30] The quality and nutritive value of date fruits are influenced by external and internal changes during maturation.[31] The edibility of date fruits spans the last three stages due to reduced bitterness, increased sweetness, improved tenderness, and juiciness.[10,24,32] It is noteworthy to reiterate that the chemical and functional contents of dates are affected by the different stages of growth (Table 1) evinced by the simultaneous reduction in fibers, vitamins, and minerals as sugar levels increase, resulting in a total decrease in weight.[33,34] Additionally, phenolics and flavonoids have been reported to decrease as dates age, especially in Ajwa dates.[35]

Dates not only serve as a cost-effective staple food source, contributing to food security in agrarian societies, but are also considered excellent sources of energy for growing populations.[36] Consumption of dates contributes to overall health due to their richness in bio-nutrients, such as dietary fibers, proteins, carbohydrates, low fat, and minerals, with carbohydrates being the most abundant, averaging an estimated 50–89 g of total sugars per 100 g of date fruits.[10,32,37] Furthermore, vitamins, such as thiamine, cobalamin, riboflavin, retinol, pyridoxine, and ascorbic acid, along with carotene, flavonoids, and anthocyanins that influence date color, have been identified in date fruits.[1,6,19] The presence of bioactive compounds like antioxidants, phenols, sterols, anthocyanins, and carotenoids, enhances the functional and health properties of dates, making them beneficial for treating cardiovascular and stomach disorders.[10,30,38–40] It is crucial to note that the composition and quantity of these micro and macro nutrients vary according to the cultivar, growth region, ripening stage, and climatic conditions.[32,37,41]

The date palm tree has garnered significant attention owing to its desirable fruits and high nutritional benefits.[42] Traditionally, all parts of the date palm tree have found applications in medicine and food, playing a unique role in the diets of residents in date-producing countries. Date palm fruits have been utilized in traditional medicine as syrups for treating liver diseases and for pregnant women just before delivery. Consuming dates regularly is believed to protect individuals from chronic, infectious, and gastrointestinal diseases.[43] Date fruits and associated products, such as date syrups, serve as raw materials for beverages, confectioneries, ice creams, and bakery products.[44]

The production of dates generates approximately 30% waste during harvesting from immature stages within the cluster. Second-class dates are also generated during picking, storing, or conditioning. Furthermore, the processing of date fruits into secondary products, such as confectionary dates, date paste, date fruit powder, vinegar, jam, chutney, date syrup, sugar, juice, and syrups, results in the generation of tons of waste in the form of fibrous date pomace (dibs) and seeds,[45,46] along with by-products like date seed flour hydrolysate (DSFH), date seed flour (DSF), defatted date seed, fermented date fruit puree, and date seed oil.[1] These by-products have industrial functional applications in food. Intriguingly, there is scientific evidence supporting the nutritional and bioactive properties of date fruits and their by-products, demonstrating antioxidant, antimutagenic, anti-inflammatory, anticancer, antimicrobial, and immunostimulant properties.[42] The global acceptance of date fruit, coupled with the aforementioned activities, contributes to the substantial amount of waste generated from date production and processing. It has become essential for farmers and processors to enhance the valorization of these by-products into value-added products, leveraging their inherent nutritional and medicinal benefits while promoting a circular economy and sustainability. Despite the global acceptance of date consumption, the exploration of the food and medicinal applications of dates and their by-products has not been fully investigated. Hence, the aim of this present review is to elucidate recent information about the history and market value, as well as to explore and generate comprehensive current scientific reports on different biocomponents, phytonutrients, and phytochemicals present in date by-products, specifically the date seeds and pomace. The novelty of this review is further strengthened by illuminating and accentuating the applications of these by-products in food industries as potential food additives, nutraceuticals, or raw materials for functional foods against increasing health and food insecurities.

2. By-products of date-fruit processing

Date palm holds significant socio-economic importance in countries where it is extensively cultivated, and the diverse nutritional and functional properties of the plant have led to a global increase in its production.[19,47] The date palm fruit, characterized by its cylindrical or oval shape, consists of a fleshy, thick outer layer surrounding an elongated seed with a groove on one side. The color transitions of the fruit range from yellow to reddish-brown as it matures. Renowned for their sweet taste, date fruits are highly nutritious and contain sugars, proteins, and other essential components.[32,48,49]

As one of the richest natural plant protein sources, date fruits have versatile applications in various food processes, serving as solubilizing, gelling, stabilizing, emulsifying, and foaming agents.[48] Notably, almost every part of the date fruit is utilizable. Harvested dates are consumed directly in their natural stages, such as Khalal, Rutab, or Tamer.[19] Additionally, low-grade or excess dates undergo direct processing or value addition for consumption, manifesting as date syrup, date juice, date extract, date powder, date paste, date fiber

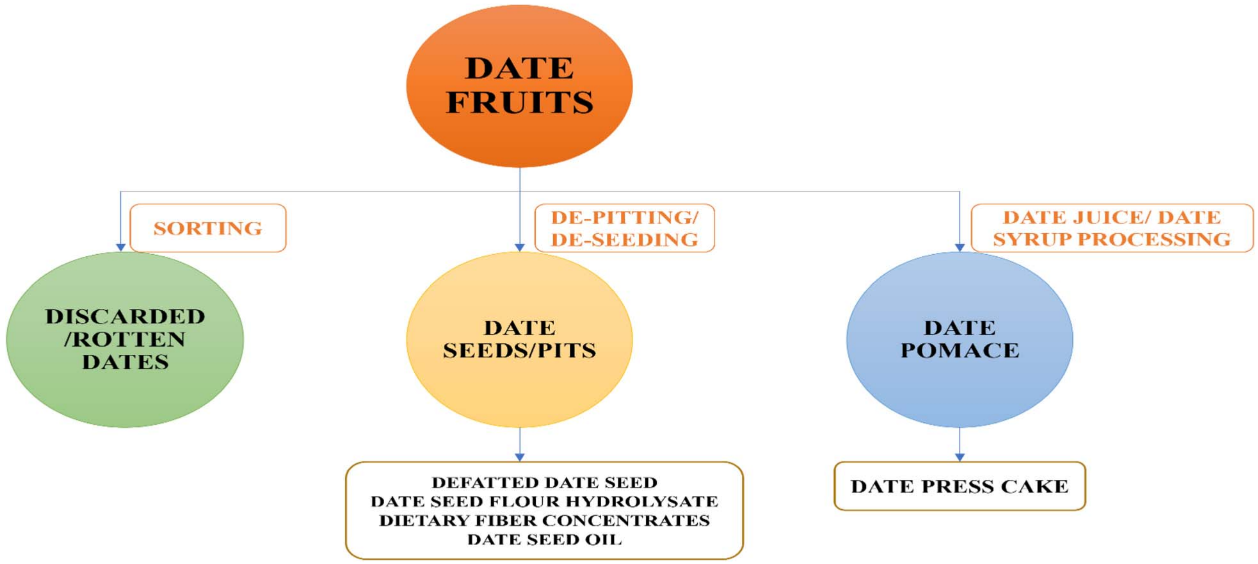

Fig. 2 Major processing by-products of date industries.

concentrate, date jam, vinegar, and some components that serve as animal feed.[50] Despite numerous efforts to convert industrially relevant date processing waste into value-added products, a substantial amount of waste is generated in the form of date seeds, date pomace, and discarded dates.[51] Fig. 2 illustrates the by-products produced by the date processing industry.

2.1 Date seeds

Date seeds are characterized by a thick endosperm and a small embryo.[52] These seeds, also referred to as pits, kernels, or stones, constitute by-products of date processing and packaging, accounting for approximately 10–15% of the total weight of date fruits.[47] The seed is composed of a small embryo and a hard endosperm, exhibiting an oblong and grooved ventral structure.[53] In their raw form, date seeds possess a characteristic brown color and a bitter taste, and are generally odorless.[54] Upon roasting and milling, they develop an aroma reminiscent of roasted coffee, with the former process improving their chemical profile.[55]

Studies focusing on the nutritional profiling of date seeds have undertaken comparative analyses of different seed varieties, maturity stages, and geographical locations.[56–58] Unfortunately, large quantities of date seeds are discarded by date industries, contributing to post-harvest waste annually.[59] Notably, date seeds exhibit the potential to remain dormant for extended periods and can grow under favorable circumstances.[60] Owing to their bioactive compounds and dietary fibers, date seeds emerge as suitable candidates as raw materials for fiber-based foods. They are rich in phytochemicals, such as phenolic acids, carotenoids, flavonoids, anthocyanins, and lignin.[61–63]

Date pits, whether in whole or roasted form, are well-known sources of various classes of phenolic compounds. A study by Ardekani *et al.* (2010)[64] highlighted that date seeds exhibited an overall antioxidant activity of 37 mmol ferric per 100 g sample and an overall phenolic content of 3658 mg gallic acid equivalents per 100 g sample. Habib *et al.* (2014)[65] reported the presence of families of phenolic compounds like phenolic acids, flavan-3-ols, flavones, flavonols, and hydroxycinnamic acids, in the UPLC chromatogram of date seeds. The concentration per 100 g of ellagic acid, benzoic acid, cinnamic acid, and pyrogallol, as identified in date seeds, ranges from 36% to 58%.[53]

Roasted date pits have demonstrated a maximum inhibiting effect against colon cancer cell lines possibly due to their phenolic profiling and antioxidant potential. Various studies have reported the role of dietary flavonoids in suppressing tumor cell proliferation.[66–68] This suppression is achieved by (i) modulating reactive oxygen species (ROS) to scavenge enzyme activities; (ii) arresting the cell cycle; and (iii) inducing apoptosis, thereby suppressing cancer cell proliferation. A study by Akasha *et al.* (2016)[48] identified storage proteins glycinin and b-conglycinin as the prominent date seed proteins out of the 300 proteins detected. The protein found in date seeds contains a higher concentration of sulfur-containing amino acids, such as methionine and cystine and negligible concentrations of tryptophan. This concentration and type of amino acid vary with different date cultivars and processing methods. For example, in roasted date seeds, the highest reported amino acids were glutamic acid, arginine, aspartic acid, and leucine, corresponding to 16.44, 8.13, 7.63, and 6.10 g/100 g proteins, respectively.[69]

Date pits were traditionally discarded during processing until recent times when their potential functionalities were explored. Powdered seeds have been used as caffeine-free coffee ingredients in the Arab world for decades. In recent times, date seeds have found applications in animal feed, enhancing animal growth by boosting hormone levels.[70] Extensive studies are ongoing on the utilization of date seed by-products in foods owing to their physicochemical and nutritional properties. A positive trend in world date production is observed every year, emphasizing the importance of exploiting date pits containing numerous bioactive constituents for the benefit of mankind and as an extended income for this sector.[55] As the major by-product of date processing industries, date seeds are utilized in different forms based on their nature of applications, such as defatted date seeds, date seed flour hydrolysate, dietary fiber concentrates from date seeds, and date seed oils.

Date seeds contain a comparatively higher proportion of dietary fibers, approximately 70%, compared to pulp. The major components of these dietary fibers are insoluble, with a lower proportion being soluble. The dietary fibers in date seeds primarily consist of cellulose and hemicellulose, mainly gluco and galacto-mannans.[71] The composition of these fibers, along with their water and oil holding capacity and emulsifying abilities, has paved the way for their application in foods fortified with natural fibers.[70]

It is estimated that, on average, 3900 tons of date seed oil could be extracted from date pits annually.[72] The superior quality of date seed oils is attributed to their lower acidity and peroxide values compared to refined vegetable oils, such as sunflower oil, indicating their lower oxidation potential. Furthermore, the oil derived from date seed extraction is rich in monounsaturated fatty acids and lipid-soluble antioxidants like phenols and phytosterols, which have the potential to lower the likelihood of various diseases.[73]

The oil extracted from date seeds contains more saturated fatty acids than unsaturated ones, with oleic and linoleic acids being the major mono-unsaturated fatty acids, and lauric, myristic, and palmitic acids being the major saturated fatty acids. The ratio of oleic to linoleic acids determines the quality of the extracted oil.[69,74] Oleic acid is generally considered advantageous for health due to its low saturation level, *trans*-isomer content, and its ability to act against increasing LDL cholesterol levels. The physicochemical characteristics of the oil hint towards its oxidation and thermal stability, making it a suitable candidate for use as edible oil.[72]

The oxidative stability of seed oil is explained in terms of its higher average tocopherol content, observed in date seed oils compared to olive and peanut oils. The key mechanism governing this is the ability of date seeds to scavenge free radicals, thereby protecting cells from oxidative stress. Carotenoid, a phytochemical in the form of β-carotene, is present in date seeds and oil in major quantities. The quantity of carotenoid is considered an important parameter for assessing the oil quality, as this phytochemical directly correlates with the color of the oil.[36,53] Given the annual global wastage of date seeds, the date seed oil resulting from extraction is a promising potential ingredient in the food, medical, pharmaceutical, and chemical sectors.

2.2 Date pomace

Date pomace, a by-product of the date syrup industry, constitutes approximately 50% of the weight of date syrup.[75] Date fruit pomace, generated during the production of date products such as pitted dates, date syrup, and confectionery, is a readily available and cost-effective substrate with a high content of reducing sugars, approximately 35%.[45,76,77] Hot water-assisted extraction of date syrup leaves behind 8–15 g/100 g and 17–24 g/100 g date seeds and date fruit pomace, respectively, as major industrial wastes.[78,79] Similar to date seeds, date fruit pomaces from syrup processing units, consisting of exhausted date flesh and residual sugars, are released in huge quantities annually, either being dumped into open lands as industrial waste or used in animal feed.[80,81]

Date pomace is an excellent source of dietary fiber, protein, residual sugars, and fat, with the former around 45 g/100 g of dry weight, making it a potential polysaccharide source.[82] It also contains microelements, such as manganese, calcium, iron, zinc, magnesium, and potassium, in the range of 10.9–625 mg kg^{-1}, respectively, along with carotenoids.[83,84] Dietary fiber in pomace comprises non-starch polysaccharides, such as arabinoxylans, cellulose, and other constituents like resistant starch, inulin, lignin, chitins, pectins, beta-glucans, and oligosaccharides. The antioxidant potential of pomace is explained by its total phenolic content in the range of 170–260 mg gallic acid equivalents GAE/100 g,[45] 151 mg/100 g,[81] and by the presence of associated phenolic compounds, such as flavonoids, phenolic acids, quinones, sterols, and anthocyanins.[84] Further characterization revealed that fructose was the main simple sugar and that oleic acid was the prominent fatty acid in date pomace.[85]

Date press cake, another by-product of date syrup processing, has been largely underutilized in the food industry and consists of a mixture of fibrous material from date flesh and crushed date seeds. It is characterized by its light brown powder-like appearance owing to natural pigments like carotenoids and anthocyanins, present in date seeds and fruit. In studies on fully ripe Shahani date fruits in Iran, Majzoobi *et al.* (2019)[85] observed that date press cake is moist and contains carbohydrates (79%), crude fiber (11%), protein (6%), and fat (4.9%). Despite the low fat content, in-depth lipid profiling has shown the presence of higher levels of monounsaturated fatty acids, such as oleic acid. Phenolic compounds are in the range of 17.79 mg GAE per g, and flavonoids in the form of quercetin represent 1.89 mg quercetin per g flavonoids in the press cake, possibly hinting towards their antioxidant potential. The quantity of the most bioactive components in press cake varies with the part from which they are extracted and is strongly influenced by the date pressing/juicing process.[79]

3. Application of date by-products in food applications

3.1 Date pomace as a functional ingredient in food formulations

The suitability of using date fruit and its by-products for health-promoting functional food formulation is gaining attention in the scientific community, attributed to the diverse groups of inherent phytochemicals present in them. Date pulp, rich in critical nutritional and health-promoting contents, such as vitamins, minerals, polysaccharides, polyphenols, and proteins,[86,87] is considered an important component of the human diet.[8] Although traditionally consumed directly, the increased interest and knowledge about bioactive products and nutritional value have led to the processing of dates into various products like date juice, jam, sugar, and syrups. However, this processing generates about 1.5 million tons of waste annually, including date pomaces (DP), posing a disposal challenge for processors.[88]

DP is an underutilized co-product of date processing, composed of moisture and residual sugars from date pulp, containing a significant amount of organic compounds.[50,85,89] Currently, there are limitations to the utilization of date pomaces. Production statistics estimate that date syrup generates about 52–64% of date syrup, 17–24% of fibrous DP, and, finally, 8–15% of date seeds.[79] Presently, some generated pomaces from the date processing industries are used either as animal feeds or feed additives, while significant amounts end up in landfills. Unfortunately, these wastes contain a substantial amount of moisture and organic compounds that degrade, forming leachate and offensive odors that cause environmental pollution.[80,90] The deposition of these pomaces in the environment raises concerns for global waste management, sustainability, and public health, given the inherent ecological threats and the potential spread of diseases due to bacteria, pests, and rodent survival.[80,91]

As a by-product of date processing industries, date pomace (DP) has been documented to be rich in valuable residual biomacromolecules, macro and micronutrients, and oxidation inhibiting agents.[46,92,93] Fig. 4 illustrates the different valuable components of DP. Specifically, Iranian Shahani date fruit pomaces were evaluated by Majzoobi *et al.* (2019)[85] to contain 79.1% carbohydrate, 11.7% crude fiber, 13.4% moisture, 4.9% fat, and 6.3% protein. Despite the abundance of valuable biomacromolecules, DP remains one of the underutilized fruit by-products, especially in the food industry. Researchers have identified a lack of technical knowledge about the health, nutritional, and potential effects of DP on overall food quality as major limitations hindering the use of DP as a functional ingredient in the food industry.[83,85,94]

Currently, there is increasing research on DP valorization as a microbial fermentation substrate. Interestingly, DP is rich in antioxidants and dietary fibers that can be incorporated into different food products as functional ingredients while promoting the principles of the circular economy and sustainability. This approach will not only foster the production of functional and healthier foods but also reduce morbidity and mortality due to degenerative diseases such as diabetes, cardiovascular diseases, and cancer. Examples of such functional and healthier foods include bakery, confectionery, and dairy products.[95] The incorporation of date and its by-products into foods, such as meat, cheese, bakery products, pastries, and cheese, has been documented in the literature.[21] Table 3 shows different food products fortified with date pomace as raw materials or supplements.

Overall, bakery and pastry products have been extensively formulated using DP as functional ingredients to replace sugar and flour or to act as a source of fiber to improve the sensory, nutritional, and physicochemical properties of the products. Generally, bakery products, such as bread, cookies, cakes, and biscuits, have a high glycemic index (GI). Interestingly, accumulated evidence suggests that fortification of these products with fruit and vegetable by-products correlates with reduced GI owing to enhanced digestion of the carbohydrate component by the soluble fibers and phenolic compounds present in the by-products.[54,96–99] All the fortified food products reported in Table 3 have shown improved nutritional, sensory, rheological, and physicochemical properties due to the incorporated date pomace. Bchir *et al.* (2014)[100] highlighted some potential mechanisms by which DP improves dough performance and bread quality in their study. The increased water absorption (55–60%) and dough volume (166–169 g) were attributed to the hydrogen bonding of the hydroxy groups of date pomace dietary fibers and water. Similarly, an increased dough gelatinization temperature ranging from 66.4 to 69.6 °C was reported to result from the competition between incorporated DP and starch for water, leading to a decrease in water absorption and an increase in dough gelatinization temperature. The interaction of DP with flour protein interrupts the starch–gluten complex, increasing dough stability from 4.0 to 31.0 min, which indicates good dough strength. Additionally, the reduced dough viscosity and extensibility were associated with starch–gluten complex interruption and DP-flour protein interaction, respectively.[100] Date pulp was supplemented in bread as a sucrose alternative by Nwanekezi *et al.* (2015).[101] The authors concluded that the nutritional characteristics measured in relation to dietary fiber and protein significantly increased with an increase in date pulp quantity.

Biscuits are an essential product of the food industry and are consumed as snacks or desserts. Currently, consumers are skeptical about the consumption of biscuits owing to their high sugar and fat contents, leading to them being labeled as unhealthy foods.[102,103] To address this concern, researchers have suggested that fortifying ingredients and proportions with fruits and vegetable by-products containing bioactive phytochemicals can help produce biscuits that meet the requirements of healthy and functional foods for the prevention of chronic diseases, health maintenance, and promotion.[104,105] Based on previous studies on the fortification of food products with date pomace (DP), Sheir (2022)[83] investigated the potential of formulating vegan biscuits and protein bars. The author concluded that the use of DP in producing vegan biscuits and protein bars has economic and health value, especially for athletes, vegetarians, and adolescents, owing to the high content of recommended dietary allowances as well as the nutritional, sensorial, and physicochemical properties of the products.

Cookies, another essential bakery product with a longer shelf life, high energy, and global consumption as a quick snack, are characterized by low moisture, resulting in comparatively low microbial spoilage and enhanced shelf stability.[106] Similar to biscuits, cookies are often rich in high sugar, which is associated with metabolic disorders, raising concerns about their consumption among certain age groups. The use of commercial wheat or composite flour has been criticized as “slow poison” owing to refining and bleaching.[107] Ajibola *et al.* (2015)[108] reported the practicability of fortifying cookies with ingredients, such as fruit by-products, tailored to the nutritional and therapeutic requirements of consumers. Considering the abundance of biological macromolecules in DP, especially residual sugar, Ikechukwu *et al.* (2017)[107] utilized DP as a sucrose replacer in cookies, with the fortified products considered ideal for patients suffering from metabolic disorders and as functional foods. The authors concluded that the inclusion of DP as a sugar replacer in cookies improved the flour functional properties, as well as the physicochemical and proximate properties of the cookies.

There is an increasing campaign for the reduction of animal protein and fats, with a focus on the increased consumption of cereals rich in dietary fiber by health authorities.[109,110] Similarly, the consumption of pasta as a cereal product has been recommended as a nutrient supplement by the World Health Organization.[111] Traditional pasta is deficient in required nutrients that can foster a positive health status in consumers.[112] Researchers have proposed the use of non-durum wheat flour with dietary fiber-rich ingredients to produce tailored pasta with functional properties for health promotion and maintenance. In the past, legumes and other cereal flours have been supplemented for pasta production, increasing the tenacity and quality of products.[111–113] Recently, Bchir *et al.* (2022)[110] formulated a new pasta product from DP flour. The authors concluded that DP positively influenced the physicochemical properties, sensorial and organoleptic properties, as well as cooking quality of the fortified pasta. In particular, DP inclusion increased the fiber content, swelling index, and cooking water absorption of fortified pasta while significantly reducing the optimum cooking time. Another researcher also included DP as a source of dietary fiber in yogurt, where it was observed that DP inclusion reduces syneresis while improving whey retention, textural, and sensory properties of the yogurt.[114]

The modification of products with date by-products has been a subject of debate among researchers, with some arguing that it may impact the overall quality of new products.[115] Consequently, studies evaluating sensory aspects and product quality indicators, such as texture, aroma, and flavor, have been conducted. In summary, most of these studies have reported positive quality parameters, including color, texture, and aroma, as well as high consumer acceptance of modified products.[116]

For instance, Sánchez-Zapata *et al.*, (2011)[35] found improved sensory quality in meat products treated with date by-products. Similarly, Martín-Sánchez *et al.*, (2014)[34] reported that technological and sensorial characteristics remained unchanged in dry-cured sausage treated with 5% date by-products paprika compared with the traditional prototype. Another study focused on sausages incorporated with date pomace powder also confirmed satisfactory sensory and technological properties, with a high acceptance rate from the panelists.[117]

3.2 Potential applications of using date seeds in food products

Date pits are recognized for their substantial content of fiber, tannins, and, potentially, resistant starch, which may offer notable health benefits. They are considered an excellent source of dietary fiber, with total dietary fiber ranging from 63.81 to 80.2 g per 100 g, of which 53–55 g/100 g consists of insoluble dietary fiber, including hemicellulose, cellulose, and lignin.[61,69,118–120] According to Hamada *et al.* (2002),[61] date pit fiber is reported to have a higher percentage of approximately 65–69% neutral detergent fiber, suggesting the possible presence of lignin and some resistant starch. Dietary fiber encompasses several health benefits, including its effectiveness against hypertension, coronary heart disease, elevated cholesterol levels, cancer, and digestive issues, as demonstrated by various studies.[120–122] The primary components of dietary fiber polysaccharides are β-glucan, arabinoxylans, and cellulose. Dietary fibers play a crucial role in the food and therapeutic industries, particularly in the baking and confectionery sectors. The increasing demand for these fibers stems from their advantages, such as antidiabetic, anti-obesity, cholesterol absorption limitation, and gut microbiome-promoting potential.[123] Notably, fibers in date seed powder have been reported to have potential therapeutic effects for lifestyle diseases, such as diabetes, obesity, and hyperlipidemia. Laboratory rats treated with date seed extracts exhibited improved glucose tolerance, reduced levels of creatinine and alkaline phosphatase and showed no signs of acute cytotoxicity, suggesting the anti-lipidemic and anti-diabetic potential of seeds.[124] Date seeds are effectively hydrolyzed by bile acids to release adequate dietary fibers in the diet.[125] The prominent dietary fiber content in date seeds and their effective release into the human system extend their application in functional foods and dietary supplements. Additionally, date seeds contain various minerals, including sodium, iron, magnesium, potassium, calcium, zinc, manganese, copper, cobalt, and cadmium, among which sodium, potassium, and magnesium constitute the major part.[49] The utilization of date seeds as a food ingredient is further supported by the absence of antinutritional components in the seeds, preventing interference with minerals and protein in the body.[126]

Antioxidant activity is primarily explained by the phenolic content of plants. Plant-based phenolic compounds, serving as natural sources of antioxidants, are considered excellent candidates for delaying the lipid oxidation reaction in foods.[64] This preservation action helps maintain nutritional quality and extends the shelf stability of food products. In comparison to synthetic antioxidants, natural phenols preserve the taste and flavor of fortified food products. Additionally, phenolic compounds have the potential to act as antimicrobial agents that are effective in modifying intracellular pH, chelating metals essential for microbial viability, and altering microbial cell membrane permeability.[127]

Date seeds exhibit a range of beneficial properties, as reviewed by Maqsood *et al.*, 2020,[36] including antioxidant activity by inhibiting lipid peroxidation and scavenging free radicals; antibacterial activity by inhibiting the growth of both major Gram-positive and Gram-negative bacteria; antifungal activity, particularly against *Fusarium* oxysporum; anticancer activity by inhibiting cell proliferation in tumor lines; anti-hyperglycemic activity by regulating glucose levels, performed by protocatechuic acid and caffeic acid; and anti-inflammatory activity *via* the aid of rutin, quercetin, *p*-coumaric, and caffeic acids.[128–130] Additionally, date palm pit extracts tested for their antiviral effects against lytic *Pseudomonas* phage ATCC 14209-B1 clearly displayed antiviral properties of extracts, with a minimum inhibitory concentration (MIC) of less than 10 mg mL^{-1}, limiting the infectivity of the phage and completely preventing the lysis of bacterial cells.[131] This finding raises the prospect of exploring industrial waste as a potential novel functional ingredient in food systems.

Most recent studies have focused on replacing synthetic functional food ingredients with date by-products with comparable activities. Nowadays, the valorization of by-products from the food industry by reincorporating them into the food chain is one of the main approaches used to improve the sustainability of food production through the reduction of the amount of waste generated, thus promoting a circular economy. Some of the potential applications of date seeds in their natural and modified forms in different food sectors are presented in Table 2. The utilization of date seeds (raw, roasted, powdered, and defatted) and their secondary products, such as dietary fiber, and oils, has been reported by researchers in bakery and confectionery,[132,133] beverage,[134] meat, dairy, and among the major industrial food sectors (Fig. 3).

The significant application of date seed by-products is evident in the bakery and confectionery sectors, leveraging the potential functionality of the seeds and offering considerable value-addition potential. The current trend in the food industry is a shift towards natural, green ingredients and processes, replacing conventional ones. The contemporary lifestyle, characterized by a fast-paced environment and a preference for instant, ready-to-eat, and value-added products, has particularly benefited from industrially relevant date seed wastes. Loaves of bread supplemented with water-soluble polysaccharides and hemicellulose extracted from date seeds demonstrated improved functional qualities, enhancing emulsification, water and oil holding, and foaming properties. This improvement led to significant enhancements in the rheological and textural properties of dough.[132] This study suggests that date seed components, particularly seed fibers, could effectively enhance the functional properties of baked goods.

Another investigation by Amin *et al.* (2019)[135] delved into cookies incorporated with date powder. The resulting cookies, except for those with 10% powdered date seeds, showed reduced diameter, thickness, and spread ratio, negatively affecting the textural properties of the cookies. Najjar *et al.* (2022)[133] developed cookies by substituting wheat flour with date seed powder at three different levels (2.5%, 5.0%, and 7.5%) and baking at distinct temperatures (180 and 200 °C). The composite cookies revealed notable total phenolics and flavonoids, imparting enhanced antioxidant potential to the cookies. Traditional pan bread supplemented with 5%, 10%, and 15% date pit powder was developed and studied by Halaby (2014).[136] The results indicated that loaves of bread with 15% added seed powder were more accepted compared to the control and other formulations. When tested on rats, the fortified bread showed significant reductions in blood glucose, glycosylated hemoglobin, LDL, and HDL cholesterol levels. Dietary fibers from date seeds obtained by defatting date seed powder were studied as a novel source of dietary fiber.[137] Comparative studies of date seed dietary fiber and commercially available fiber from sugar beet residues suggest that the former is superior in terms of dietary fiber content, purity, and richness. However, studies on the partial substitution of both fibers in the same range (2.5% and 5%) of wheat flour for bread production revealed that bread fortified with 2.5% of both fibers was not significantly different from control bread with no fiber content. These findings highlight both the potential benefits and challenges associated with incorporating date seed derivatives into baked food products, emphasizing their impact on different physical and functional properties.

Coffee and tea stand out as the most preferred beverages worldwide. However, ongoing debates question the healthiness of these beverages for all population sectors. Pregnant women and children, in particular, are advised to limit their caffeine consumption, which is higher in coffee. Coffee with a high caffeine content is reported to have major side effects, such as sleeplessness, nervousness, and an increased heart rate.[138] Recently, there has been growing interest in studying alternative coffee beans to mitigate these well-known adverse effects. Studies have explored the full or partial replacement of coffee with date seed powder to develop coffee-like healthy beverages. Three different types of coffee were made using roasted date pit powder and other functional additives, C1 (roasted date pits alone), C2 (date pits, cardamom, button roses, nutmeg, and cloves), and C3 (date pits, barley, cardamom, button roses, nutmeg, and cloves), all of which had a higher nutritional value compared to commercial coffee.[138] The caffeine content of C3 was significantly lower than that of commercial coffee, with 2.99 mg g^{-1} in the former and 36.02 mg g^{-1} in the latter, whereas the antioxidant activity of C3 was higher than that of the rest of the samples. Notably, despite the low caffeine content, C3 was best accepted in sensory trials, outperforming commercial coffee.

The production and consumption of meat and meat products present significant challenges to the food industry, with a growing emphasis on quality and safety for both manufacturers and consumers. Essential aspects determining consumer perception of meat, such as tenderness and juiciness, are closely linked to meat oxidation. Date seeds exhibit the potential to prevent collagen and lipid oxidation in meats owing to the presence of phenolic compounds, such as tannins.[24] Condensed tannins form hydrogen bonds with meat proteins, acting as antioxidants and preserving meat tenderness.[139] This concept was applied by Nor *et al.* (2022)[140] in a study on the tenderizing effect of date seed powder on lamb and beef. The addition of date seed powder resulted in a reduction in the major textural properties of marinated lamb and beef samples compared to the control, with a comparable decrease in water holding capacity and cooking loss in meat samples with increased date seed powder.

Another noteworthy effect was observed in the improvement of shelf life and bioactivity of marinated fresh meat by date seed extract, as investigated by Abdelrahman *et al.* (2022).[141] Meat samples treated with 2% seed extract showed an overall

Table 2 Various applications of date seeds in food products

Sector of application	Product type	Nature of date pit	Effective level/ percentage	Quality attributes impacted	References
Beverage	Coffee	Roasted and powdered date pit	9%	9% roasted date seed powder is a coffee substitute with coffee-like properties and fewer health risks	Venkatachalam and Sengottian (2016)[232]
	Coffee-like beverages	Roasted and powdered date pit	N.A	The beverage had lower total phenolics, antioxidants, color, bitterness, and coffee flavor than traditional Arabic coffee	Ghnimi *et al.* (2015)[233]
	Coffee	Roasted and powdered date pit	C1-100% C2-92.5% C3-61.67%	Date pit coffee with additives had low caffeine content, no cytotoxicity, high nutrition, antioxidants, and acceptability exceeding control coffee	Ragab and Yossef (2019)[138]
	Cocoa substitute beverage	Roasted and powdered date pit	9%	Water–milk with roasted date seeds was preferred over cocoa. It has potential health benefits	El Sheikh *et al.* (2014)[69]
Bakery and confectionary	Enriched bread	Powdered date pit	4–12%	Date pit powder added to bread increased soluble fiber, while wheat flour blended with 12% date pit powder resulted in higher firmness	Alamri *et al.* (2014)[234]
	Bread	Powdered date pit fiber	10%	Bread with higher dietary fiber content can be made to have a comparable sensory profile to wheat bran bread	Najafi (2011)[119]
	Bread	Intact and defatted date pit powder	5, 10, and 15%	Date pit powder improved water absorption and dough efficiency. 5% in bread created a unique sensory profile	(Khodaparast *et al.*, 2007)
	Pita bread	Date pit powder	Flour substituted with 5, 10, 15 and 20% date seed powder	Fortified bread had comparable dietary fibers, increased flavonoids, phenolic compounds (flavan-3-ols), antioxidant potential, and limited acrylamide content compared to whole wheat bread	Platat *et al.* (2015)[162]
	Mayonnaise	Date seed oil	NA	Date seed oil in mayonnaise outperformed corn oil for better sensory qualities	Basuny and Al-Marzooq (2011)[145]
	Butter cake	Date seed powder	2.5%	Butter cakes with 2.5% ground date seed powder exhibited similar sensory and nutritional properties but had negative bulking, pasting, and baking characteristics	Ammar *et al.* (2013)[235]
	Cookies	Fine seed powder	2.5–7.5%	Seed powder influenced cookie lightness and hardness; higher additions resulted in darker and crispier cookies. Cookies with 7.5% seed powder in whole wheat flour showed the highest acceptability	Najjar *et al.* (2022)[133]
	Chocolate spread	Dietary fiber from seeds	5%	Seed powders enhanced water and oil binding capacity, emulsion stability, and overall acceptability	Bouaziz *et al.* (2017)[236]
	Baker's yeast	Date seed hydrolysate	3% w/v of date seed hydrolysates, rice straw, and date flesh as carbon source	9.12 g L^{-1} baker's yeast obtained after 18 h fermentation with *Saccharomyces cerevisiae* at 30 °C	Salem *et al.* (2016)[237]
Meat and poultry	Cooked ground beef	Date pit extract	0.5, 0.75, and 1%	Khalas date pit extract enhanced minced beef with potent antioxidants, phenolic content, TBA reduction potential, and superior sensory characteristics	Amany *et al.* (2012)[238]
	Beef burger	Date seed powder	1.5, 3, and 6%	Beef burgers fortified with seed powder exhibited improved cooking and sensorial properties, lower lipid oxidation, and microbial contamination during shelf-life	Sayas-Barberá *et al.* (2020)[116]
	Beef burger	Date seed powder	25, 50, 75, and 100%	Replacing breadcrumbs with 25% date seed powder led to reduced lipid oxidation, microbial contamination, and improved cooking properties and sensory acceptance in burgers	Alqahtan *et al.* (2022)[239]
Dairy	Spreadable processed cheese	Date seed powder	0, 1, 5, and 10%	Fortified cheese with 1% and 5% seed powder showed significant differences in total solids and fiber contents, with favorable sensory acceptance	Darwish *et al.* (2020)[240]

Table 2 (*Contd.*)

Sector of application	Product type	Nature of date pit	Effective level/ percentage	Quality attributes impacted	References
	Processed cheese	Fiber from date seeds	0, 5, 10, 15, and 20%	Partial substitution of butter by date seed fiber in processed cheese positively impacted nutritive value but negatively affected texture. Cheese with 5% and 10% seed fibers showed overall acceptability	Alqahtani *et al.* (2023)[146]
	Kareish cheese	Date seed powder	0.5, and 1%	Kareish cheese supplemented with date seed and oat fibers showed improved storage characteristics, resulting in higher yield and total solid content with reduced coagulation and setting time	Basiony *et al.* (2018)[241]
	Prebiotic	Date pit	NA	Fiber-fortified Kareish cheese demonstrated an increased presence of lactic acid bacteria and bifidobacteria, suggesting a potential probiotic effect with overall acceptability in flavor and texture	Khiyami *et al.* (2008)[242]
	Probiotic yoghurt	Date seed powder	0.5%	Date seed powder as a natural stabilizer in set yogurt positively influenced the growth of Lactococcus lactis, enhancing rheology and sensory attributes. Increased seed powder concentrations led to decreased titratable acidity and excellent water holding capacity during storage	El-Kholy (2018)[243]

reduction in total volatile nitrogen, TBAR level, and aerobic bacterial counts compared to the control, extending the shelf life and preventing the growth of pathogenic strains, such as *Salmonella* and *Campylobacter*. Essa and Elsebaie (2018)[142] proposed another application of date seed powder as a fat replacement agent in meat products. Burger samples with date pit powder (25%, 50%, and 75%) as a substitute for animal fat exhibited improved nutritional, functional, and cooking quality of beef burgers. The substitution retained fat and moisture, crucial attributes for consumer satisfaction, and demonstrated greater stability against lipid oxidation, associated with higher polyphenol contents. Bouaziz *et al.* (2020)[70] formulated low-fat turkey burgers with Deglet Nour date seed flour at various concentrations (3%, 5%, and 10%), demonstrating that burgers made with up to 5% date seed flour had similar textural properties and improved sensory attributes (texture, flavor, and overall acceptance) compared to control samples.

Moreover, the insoluble dietary fibers in date seeds were investigated owing to their potential to improve the techno-functional properties of meat products. The addition of fibers resulted in a considerable reduction in calorie content and an improvement in the texture and quality of meat. For instance, Abdel-Maksoud *et al.* (2022)[143] studied the addition of date seed powder at different levels (0–16%) to beef meatballs, revealing improvements in nutritional, technological, and overall physicochemical characteristics without significant alterations to the sensory qualities of the beef meatballs. The phenolic and antioxidant potential of date seeds prevented the oxidation of native fat in meat to a certain extent. In conclusion, these studies collectively highlight the versatile applicability of date seeds and their co-products in improving and maintaining the quality and nutritional aspects of meat products.

Moving on to polyols, a class of sugar-free sweeteners containing multiple hydroxyl groups, they are employed in food products owing to their lower calorie content compared to sugars. Polyols from date pits were developed through an oxypropylation reaction of natural polymeric material found in date seeds *via* liquefaction using organic solvents and a catalyst.[144] The oil extracted from leftover pits of the Khalas date variety was utilized as a substitute for traditional corn oil in mayonnaise (an emulsion of oil and egg yolk). The mayonnaise containing date pit oil exhibited better sensory qualities compared to commercial mayonnaise, supporting the notion of employing date pit oil as an unconventional choice for making mayonnaise products.[145] In a study conducted by Alqahtani *et al.* (2023),[146] date seed powder was explored as an innovative fat replacement and fiber source in processed cheese blocks. They used four different concentrations of date seed powder (5%, 10%, 15%, and 20%) to replace cheese fat, examining the impact on the cheese's chemical composition, microstructure, rheology, and sensory attributes. Partial substitution of butter with date seed fiber in block-type processed cheese positively affected the nutritive value but negatively impacted the texture profile. The fortified cheese exhibited a less compact and wider cheese network structure compared to the control. Cheese with 5% and 10% seed fibers showed overall acceptability.

Table 3 Various application date pomace in food products

S/N	Food	Uses	Product indicator	Pomace preparation condition	Concentration used	Optimum concentration used	Outcome	Reference
1	Biscuit	Flour replacement	Quality characteristics	Oven dried at 120 °C for 30 min	20, 25 and 30%	30%	Increased ether extract, ash, crude fiber and mineral content Reduced protein, carbohydrate and energy Reduced moisture content and water activity Significant reduction in pH during storage Better sensory properties and acceptability	Saleh *et al.* (2022)[103]
2	Cookies	Sugar substitute	Proximate and physical properties	Oven dried at 75 °C for 6 – 8 hours	10, 20, 30, 40 and 50%	30%	Increased swelling index, OHC, pH and viscosity Increased proximate composition except for carbohydrate and protein Increased physical properties except for break strength	Ikechukwu *et al.* (2017)[107]
3	Cookies	Flour replacement	Microstructure and functional attribute	Oven dried at 60 °C for 10–12 h	2, 4 and 6%	4%	Increase in water absorption, moisture, ash, crude fiber, protein and fat content Decrease in spread ratio, diameter, hardness and air space Increase in cookie thickness	Shabnam, *et al.* (2020)[244]
4	Pasta	Flour complement	Functional, rheological and sensory properties	Oven-dried for 7 h at 70 °C	2.5, 5, 7, and 10%	2.5%	Increased energy and fiber content Reduced cooking time, adhesiveness, and extensibility Enhanced swelling index, cooking water absorption, water activity, firmness, and tenacity of pasta	Bchir *et al.* (2022)[110]
5	Yoghurt	Source of fiber	Sensory and physical properties		2, 4, 6%	4%	Improved whey retention textural properties Reduced syneresis Improved sensory qualities Lower microbial contaminant	Hamdia (2016)[114]
6	Bread	Source of fiber	Nutritional and techno-functional properties		2%		Comparable dough volume Increased water absorption, stability, tenacity, and dietary fiber Reduced extensibility, softening, breakdown and setback More aerated internal crumb structure comparable with the control during storage	Bchir *et al.* (2014)[100]
7	Batter and cake	Flour complement	Rheological, physical and nutritional properties		10, 20, 30, and 40%. Particle sizes 210 μm and 500 μm	10% and 210 μm	Increased batter consistency, firmness, density, stickiness, cohesiveness and viscosity	Majzoobi *et al.* (2019)[85]

Table 3 (*Contd.*)

S/N	Food	Uses	Product indicator	Pomace preparation condition	Concentration used	Optimum concentration used	Outcome	Reference
							Increased cake density, hardness, and antioxidant content Reduced pH, cohesiveness, volume and crust moisture content of cake	
8	Cereal bars	Source of fiber	Physicochemical, sensory and nutritional characteristics	Oven-dried at 70 °C for 7 h	6, 10, 14%	10%	Low water activity High energy Darker color Texture parameters are comparable with the control	Bchir *et al.* (2018)[245]
9	Bread	Source of fiber	Textural properties	Oven dried at 40 °C	0.5%, 1%, 2% and 3%	3%	Reduce water activity during storage Increased hardness and firmness Springiness was comparable with the control Significant decrease in the staling rate of 1 and 3% supplementation	Borchani *et al.* (2015)[246]
10	Dough and bread	Source of fiber	Dough performance and bread quality	Oven dried at 40 °C	0.5, 1, 2 and 3% levels	3%	Increased bread yield and stability Sensory scores are comparable with the control High acceptability ratings by the consumer panel	Borchani *et al.* (2011)[247]
11	Vegan biscuits	Flour supplement	Quality and nutritional value		5, 10 or 15%	10%	Higher acceptability and physical properties compared to control Higher shelf life and recommended dietary allowance Higher moisture, protein, fiber, iron, zinc, calcium, potassium, magnesium, and manganese but lower ash and fat content Increased hardness and cohesiveness Reduced springiness, gumminess, and chewiness	Sheir (2022)[83]
12	Vegan protein bars	Flour supplement	Quality and nutritional value		10 g		Higher sensorial score in flavor, taste, texture, and overall acceptability Higher willingness to buy Higher hardness and cohesiveness while gumminess and chewiness are low Higher in protein, fiber, ash, and minerals Lower fat, carbohydrates, energy, and moisture	Sheir (2022)[83]

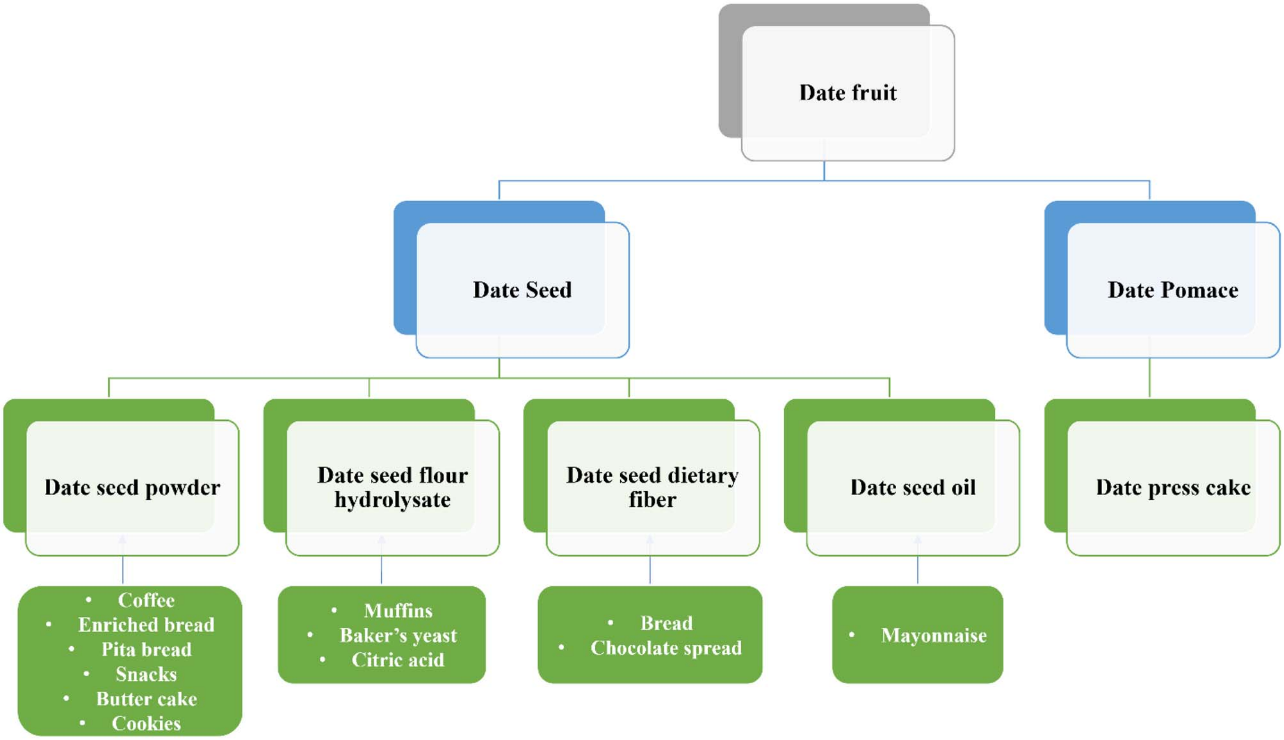

Fig. 3 Application of date seeds and their derivatives in foods.

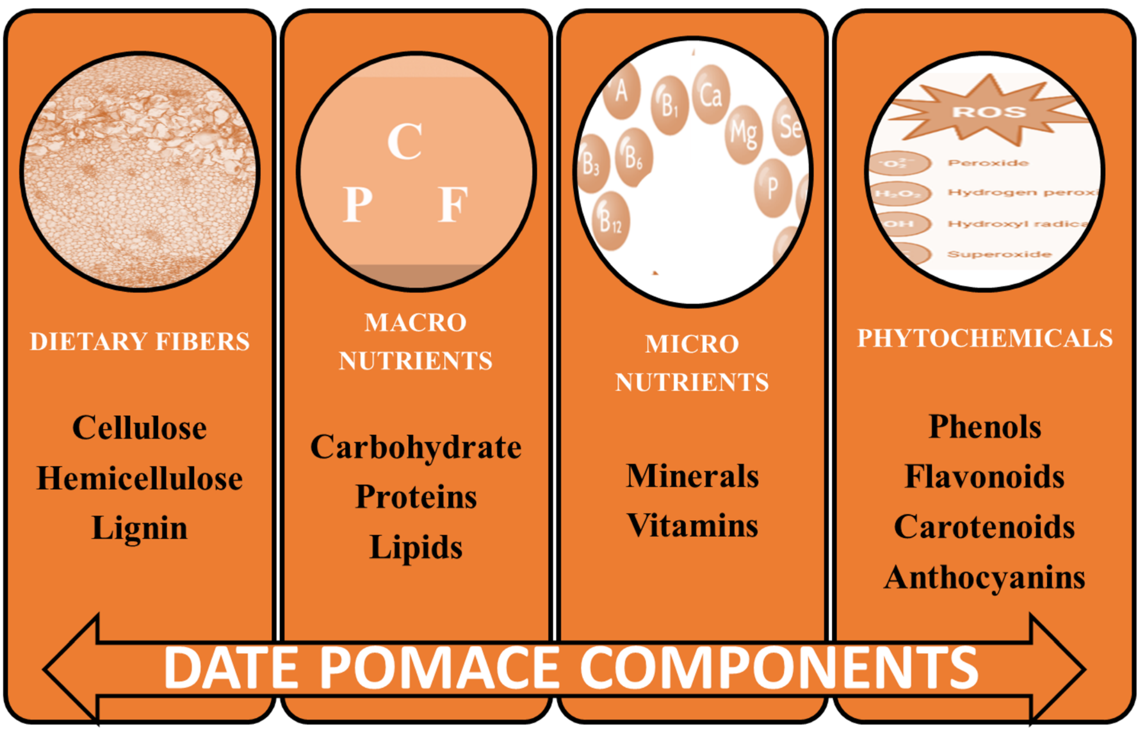

Fig. 4 Valuable components of date pomace.

Finally, the valorization of date by-products towards the development of functional yogurt was reported by Jrad *et al.* (2022).[147] Roasted date seeds (1%, 2%, and 3%) were incorporated into goat and cow milk formulations to develop functional yogurt. Roasting improved the amount of soluble fiber as well as the water holding and swelling capacity of seeds, contributing to the better texture properties of the yogurt. The functional yogurts produced were rich in proteins and appeared dark with the addition of seed powder. Overall, 3% seed powder fortified yogurts from both sources were superior in terms of moisture, protein, viscosity, antioxidant, and water holding capacity.

4. Bioactive components of date seed and pomace

4.1 Polyphenols

The richness and comprehensiveness of the available literature describing the health benefits of phytochemicals, especially polyphenols from fruits and vegetables, have captured the attention of clinicians, public health experts, and scientists, prompting their exploration in the medical, pharmaceutical, nutraceutical, and cosmetic industries Bentrad and Hamida-Ferhat (2020).[148–150] Polyphenols, as phyto-macromolecules, offer beneficial health properties when consumed as supplements or fortified in the diet (Al-Alawi *et al.*, 2017).[6] These compounds possess antioxidant properties that positively scavenge and eliminate reactive oxygen species (ROS), placing them at the forefront of research in health promotion and maintenance.[73,151]

Different parts of the date palm have been pharmacologically reported as therapeutic agents for various ailments and disorders, and date fruits have garnered considerable attention, whereas by-products are seldom reported.[152] Meta-analytical phytochemical studies of date fruits across producing countries have indicated the abundance of essential bioactive compounds in date by-products, confirming their potential as ingredients for the development of nutraceutical, cosmetic, medical, pharmaceutical, and functional food products with a wide range of health benefits.[153–155] Accumulated evidence from the literature indicates the presence of various health-promoting phytochemicals, such as polyphenols, lignin, melanin, tocopherols, anthocyanin, carotenes, tocotrienols, dietary fibers, and phytosterols, in date fruits.

Specifically, date fruits have long been proven and implicated in health and nutritional promotion owing to their richness in antioxidant-producing polyphenolic compounds that can work against oxidative stress and scavenge excess free radicals implicated in diseases such as cardiovascular, Parkinson's, cancer, and Alzheimer's diseases.[15] Ethnobotanical studies have also established the treatment of anemia, colds, sore throats, hemorrhoids, bronchopulmonary infections, jaundice, constipation, and demineralization with date pulps and syrup, while green dates are used as natural aphrodisiacs.[156] Additionally, the polyphenolic content of dates has been demonstrated to be an anticancer, antimutagenic, anti-inflammatory, and antimicrobial agent.[65,157] Researchers have correlated a reduced risk of chronic diseases and high nutraceutical values with diets rich in dietary polyphenols.[36,154]

More recently, scientists have focused on the valorization of date by-products, specifically date seeds and pomaces, owing to the abundance of similar biomacromolecules found in whole fruits.[148] The diverse polyphenols (tannins, sterols, phenolic acids, flavonoids, phytosterols, carotenoids, and volatile compounds) inherently present at high levels in dates and their by-products confirm their uniqueness from polyphenols in other fruits (such as apple, banana, red grapes, mandarin, orange, apricot, pomegranate, and blueberry).[34,158] Although variations exist in the concentration, structure, formulation, and distribution of polyphenols in date fruits depending on the cultivar, season, location, maturity, agronomic practices, and storage conditions, date and its by-products are generally rich in polyphenolic compounds that confer health benefits by scavenging and blocking the activities of free radicals and ROS implicated in the etiology of chronic human degenerative diseases, such as cancer and cardiovascular diseases.[148,151] In dates, phenolic acids and flavonoids are the major polyphenolic compounds; however, the presence of tannins has also been reported. Flavonoids and phenolic acids are important phytometabolites with remarkable antioxidant properties against ROS, promoting cellular protection against oxidative stress and damage, as well as positive health outcomes in humans.[159,160]

Researchers have meticulously documented more than 13 flavonoids and 19 flavonoid isomers in dates and their by-products, predominantly including isorhamnetin, luteolin, malonyl, apigenin, quercetin, chrysoeriol, 3-methyl-isorhamnetin, sulfates, and kaempferol, each exhibiting varying degrees of antioxidant properties.[157,161] Polyphenolic compounds, particularly flavonoids, are widely distributed in date seeds. A quantitative estimation of the polyphenolic content in three Moroccan date seed cultivars revealed a range of 1224–1844 mg/100 g of flavonoids.[130] Another study investigated the polyphenolic content of the Khalas date seed variety using mass spectrometry, reporting a total polyphenolic content of 5.1 g/100 g, significantly higher than those reported in grape seeds and flaxseeds.[162]

The abundance of flavonoids in date seeds was further documented by Habib *et al.* (2014),[65] with flavan-3-ols accounting for 99% of the total polyphenol content in date seeds. However, hydroxycinnamic acids have been identified as the most abundant phenolic acids in dates and their by-products. A study conducted by Al-Farsi and Lee (2008)[53] revealed the presence of four different hydroxycinnamic acids (vanillic acid, protocatechuic, *p*-hydroxybenzoic, and gallic) in date seeds, while Kchaou *et al.* (2016)[163] reported the presence of hydroxybenzoic acid in date flesh, underscoring the richness of date by-products in phenolic acids.

Moreover, a comprehensive study on the characterization of flavonoids and phenolic acids in date palm fruits unveiled the presence of 5 flavonoids (myricetin, rutin, quercetin, catechin, and epicatechin) and 10 phenolic acids (chlorogenic, *p*-coumaric, salicylic, gallic, *trans*-cinnamic, sinapic, ellagic, vanillic, caffeic, syringic, and ferulic).[164] Ajwa dates have been extensively studied owing to their richness and abundance of polyphenols, such as rutin, catechin, and caffeic acid, in the range of 10–290 mg/100 g depending on the fruit's maturity.[55,165,166] Total phenolic content analysis conducted by Wu *et al.* (2004)[167] revealed a range of 199.43–576.48 mg/100 g and 226–955 mg/100 g of fresh date in six Tunisian and ten Algerian date varieties, respectively.

Date polyphenolic compounds, in addition to their antioxidant properties, are known to exert various health benefits, including anticancer, anti-obesity, anti-inflammatory, antimicrobial, antiallergic, vasodilatory, cardioprotective, renoprotective, hepatoprotective, antigenotoxic, antimutagenic, and gastrointestinal protective effects.[168,169] Pharmacological studies have also correlated the consumption of date fruits with a reduced glycemic index, antiaging effects, and relief from constipation.[40]

4.1.1 Antioxidant properties of date by-product polyphenols. The escalating statistics and widespread prevalence of chronic diseases, coupled with the challenges of low potency or resistance to existing treatments and therapeutics, pose a global threat and a state of emergency in the public health domain. These concerns are exacerbated by consumer awareness of potential health risks, toxicity, and the financial implications of chemosynthetic antioxidants. Consequently, nutritional intervention through diet modification and fortification has been identified as a potential solution.[163,170]

Despite the reported richness of date seeds and pomace in valuable bioactive components, such as polyphenols, they are still treated as common waste with limited applications and underutilization. Accumulated evidence from the literature indicates that the high antioxidant activities of date seeds (DS) are attributed to their richness in polyphenolic compounds.[134,171] Thus, date by-products could be explored as a source of natural preservatives with potential applications in the pharmaceutical, medical, and food industries. Pharmacological, nutritional, and clinical evidence has positioned polyphenols as novel natural bioactive compounds, garnering attention from researchers for various health and industrial applications owing to their established antioxidant properties.[163]

Quantitatively, the polyphenolic content of DS was estimated to range from 1864.82 to 4768.87 mg GAE/100 g, while the profile analysis of the polyphenolic content revealed flavan-3-ols (catechins and epicatechins) as the most abundant polyphenols (47.91–50.18 g kg^{-1}), closely followed by phenolic acids (protocatechuic acid, *p*-hydroxybenzoic acid, and caffeoylshikimic acid).[172,173]

Researchers have correlated the abundance of phenolic acids and flavonoids in date seeds and pomaces with the observed high antioxidant potentials reported in the literature.[36,174] For instance, a study conducted in China on 28 fruits and their by-products ranked dates as the second-highest fruit with remarkable antioxidant values.[175] In a study on seeds of three Moroccan date cultivars, the authors established a strong positive correlation between phenolic acids and flavonoid contents with high antioxidant properties evaluated with FRAP and ABTS.[130]

A similar study on 100 μg mL^{-1} of aqueous and methanolic extracts from date seeds was reported by Zhang *et al.* (2017).[176] The results showed high antioxidant activities with 50–67% and 58–82%, respectively, for lipid peroxidation inhibition. The methanolic and acetonic extracts of Ajwa date seeds have been reported to exhibit a remarkable antioxidant potential of 74.19 mg per mL GA using DPPH and lipid peroxidation assays.[177]

Furthermore, an *in vitro* evaluation of flavonoids conducted by Nijveldt *et al.* (2001)[178] found that flavonoids reduce dehydroascorbic acid. Similarly, polyphenols react with superoxide anion (O-2) and hydroxyl (OH−) radicals to generate highly stable phenoxy radicals. DPPH and ABTS studies of flavonols and hydroxycinnamic acids showed high antioxidant potency against linoleic acid oxidation compared to vitamin C.[179,180]

However, date pomace (DP) has also been reported to contain a considerable amount of polyphenols and can be used as a source of natural antioxidants.[53] The effect of 100 μg of ethyl acetate extracts from Deglet Nour date flesh was evaluated by Mansouri *et al.* (2005).[181] The author concluded that there is a strong positive correlation between phenolic content and antioxidant activities, evidenced by the observed 54% antiradical activity suggested to be influenced by the high quantity of flavonoids and tannins in the extract.

The quantification and antioxidant capacities of the DP of three different cultivars of dates were investigated with the oxygen radical absorbance capacity (ORAC) assay by Al-Farsi *et al.* (2007).[79] The authors reported a remarkable quantity of polyphenols in the range of 165–435 mg of GAE/100 g of DP and antioxidant capacities in the range of 134–357 mol of Trolox Equivalents (TE) per g fresh weight of date pomace. Similarly, the half-maximal inhibitory concentration (IC50) technique was used by Majzoobi *et al.* (2020)[182] to demonstrate the antioxidant potential of Shahani DP with four different particle sizes. The authors reported IC50 values of 1.46, 1.46, 1.39, and 1.39 mg mL^{-1} for 500, 365, 210, and 167 μm of Shahani DP, respectively.

In addition to numerous *in vitro* studies on the antioxidant properties of date by-product polyphenols, there are documented *in vivo* studies highlighting the health-promoting benefits of date seed polyphenols. One such study investigated the impact of date by-products on the activities of activated inflammatory leukocytes, which are known to elicit free radicals, exacerbating diseases, such as arthritis and diabetes.[15] The effect of different concentrations of date seed consumption for 30 days on oxidative stress and antioxidant levels in male Wistar rats induced by activated inflammatory leukocytes was evaluated by Habib and Ibrahim (2011).[183] Although the serological parameters, feed efficiency ratio, hepatic antioxidants, and body weight were unaffected by date seed incorporation, the authors reported a significant reduction in serum and hepatic malondialdehyde (MDA) and dehydrogenase. The decrease in these lipid peroxidation products has been attributed to the phenolic and flavonoid profiles in date seeds.

Another study conducted by Abdelaziz and Ali (2014)[184] investigated the effect of date seed consumption on reducing nephron-oxidative stress in the kidneys of rats induced with carbon tetrachloride (CCl4). The authors reported that date seeds significantly reduced MDA and nitric oxide, restored glutathione-S-transferase and superoxide dismutase activities, and preserved kidney histology and functions, all of which are attributed to the polyphenolic contents. A robust antioxidant status, as indicated by a significant reduction in oxidative stress, was observed in the experimental rats fed with date seed-supplemented feed.[162] Similarly, Platat *et al.* (2019)[185] reported increased antioxidant activity in humans fed with date seed extract, date seed powder, and Arabic pita bread fortified with date seed.

4.1.2 Antimicrobial properties of date by-product polyphenols. The escalating prevalence of antibiotic-resistant microbes has prompted the exploration of natural antimicrobial compounds as viable alternatives. Both *in vivo* and *in vitro* studies on various date fruit cultivars and their by-products have demonstrated noteworthy antimicrobial properties.[186] Extracts from date seeds and flesh showcase antifungal and antibacterial activities and possess a substantial level of antiviral properties. For instance, acetonic date seed extracts were reported to inhibit lytic *Pseudomonas* phage ATCC 14209-B1 activity and prevent bacterial lysis at concentrations lower than 10 mg mL^{-1}.[131] This antimicrobial activity is attributed to the binding of polyphenols in the seed extracts to the bacteriophage. In a similar study, Samad *et al.* (2016)[187] reported the broad-spectrum antibacterial activities of date seed extracts, inhibiting both Gram-positive and Gram-negative bacteria, including *Salmonella typhi*, *Escherichia coli*, *Staphylococcus aureus*, and *Bacillus cereus*. Additionally, antifungal activities were observed against *Fusarium oxysporum*. Although there is clear evidence in the literature regarding the antimicrobial properties of date fruits, affirming their potential as an alternative and cost-effective approach to combating human microbial infections, further studies on the antimicrobial mechanisms of date fruit seeds and pomaces are still required.

4.1.3 Anticancer properties of date by-product polyphenols. Presently, major cancer treatments predominantly involve chemotherapy and radiotherapy; however, their documented side effects limit their reliability and use. Consequently, there is a valid exploration of effective alternatives from natural sources. Numerous polyphenols found in date fruits, including catechin, epicatechin, *p*-hydroxybenzoic acid, protocatechuic acid, and procyanidins, have documented antitumor roles in the literature.[188,189] The cytotoxic potential of date seed extracts was investigated on five different cancer cell lines (MCF-7, MDA-MB-231, Hep-G2, Caco-2, and PC-3) by Hilary *et al.* (2021).[173] The authors reported a significant reduction in the viability of MCF-7 and Hep-G2 cancer cell lines within 48 hours. Experimental studies have also shown that the methanolic extract of Ajwa dates exerts cytotoxicity against lung, breast, colon, gastric, and prostate cancer cell lines.[176] *In vitro* studies on date seed polyphenols revealed a cytotoxic effect against pancreatic cancer cell lines.[65] Similarly, date seed polyphenols have been reported to exhibit remarkable antiproliferative effects on the MCF-7 cancer cell line.[190] The inhibition of gut tumor cell proliferation and the promotion of beneficial microbiota have been associated with the consumption of dates.[41] Although there is a lack of comprehensive information on the anticancer mechanisms of dates and their by-products, some studies suggest that polyphenolic content may be responsible for the anticancer properties of dates.[36]

4.1.4 Antidiabetic properties of date by-product polyphenols. Diabetes remains prevalent among individuals of various age groups. Current treatments for diabetes management possess limitations owing to their side effects, such as the modification of genetic and metabolic pathways. Intriguingly, phyto-polyphenols have been reported to modulate intestinal glucose absorption and insulin production, effectively contributing to the management of diabetes development.[191] More specifically, compounds such as flavonoids, phenolic acids, sterols, and saponins in dates have been demonstrated to exhibit remarkable antidiabetic activities by scavenging free radicals in diabetic-induced rats.[192] Hasan and Mohieldein (2016)[193] reported the modulation of renal and hepatic functionalities attributed to the consumption of Ajwa date seed extract, and this effect has been associated with the inhibition of α-glucosidase, leading to increased intestinal and renal glucose absorption in the kidneys.[171]

4.1.5 Other biological functions of date by-product polyphenols. Date by-product polyphenols exhibit noteworthy anti-inflammatory activities. Evaluation using cyclooxygenase enzymes (COX-1 and COX-2) by Zhang *et al.* (2017)[176] revealed 26–36% and 33–41% inhibition for COX-1 enzyme and 45–48% and 48–52% inhibition for COX-2, for aqueous and methanolic extracts, respectively. Additionally, Orabi and Shawky (2014)[194] reported a significant increase in mean corpuscular hemoglobin concentration (MCHC), hemoglobin level, and mean corpuscular hemoglobin (MCH), with a simultaneous decrease in testicular malondialdehyde levels in male albino rats orally treated with 2 mL per kg per day of date seed extracts for 60 days. In another study, Amany Alsayed *et al.* (2019)[195] evaluated the effects of 1 g per kg per day of date seed nanoparticles infused in Wistar rats as a nutraceutical. The authors confirmed that treatment with date seed extract significantly reduced total cholesterol levels, C-reactive protein, and serum amyloid-alpha in the experimental group compared to the control group. Similarly, Al-Qarawi *et al.* (2004)[196] investigated the effects of aqueous extracts of date seeds on CCl4-induced liver toxicity in Wistar rats. Rats fed with the aqueous extracts of date seeds exhibited a significant reduction in bilirubin concentrations, plasma enzyme levels, and histological damage compared to the control group. The organ and serum antioxidant system of male Wistar rats fed with 2–8 g kg^{-1} of date seed powder significantly improved compared to the control. Table 4 provides a summary of the applications of date by-product polyphenols in various studies.

4.2 Polysaccharides

Polysaccharides (PSs) represent a class of biological macromolecules composed of similar or different monosaccharide units linked together by various glycosidic bonds.[197] They are the most prevalent natural macromolecular polymers and can be differentiated based on specific monosaccharide units, chain length, and branching. These compounds play a crucial role as natural bioactive components in food matrices owing to their well-established antioxidant, anticancer, antiviral, antibacterial, probiotic, prebiotic, relatively low cytotoxic, and health-promoting properties,[198,199] supporting their applications in food matrices. Naturally occurring polysaccharides exhibit diversity in their structural, functional, conformational, and biological characteristics. Researchers have proposed several extraction methods for the efficient extraction of

Table 4 Different bioactive components from date seeds and pomace

Bioactive ingredients	By-product	Extraction method	Active ingredient	Yield	Functionality	Significant findings	Reference
Polyphenols	Seeds	Methanolic	Phenolic acids	44.2 mg GAE per g	*In vitro* antioxidant, reducing power and antiradical activities	Date seeds can be used as potential functional food ingredients owing to their high content of phenolics and antioxidant capacity	Majid *et al.* (2023)[248]
Polyphenols	Seeds	Natural deep eutectic solvent-microwave assisted extraction	Phenolic acids	234.65 mg GAE per g	*In vitro* antioxidant activities	Utilization of green extraction solvents coupled with microwave-enhanced total phenolic yield and antioxidant properties	Airouyuwa *et al.* (2023)[249]
Polyphenols	Seeds	Natural deep eutectic solvent-ultrasonic assisted extraction	Phenolic acids	145.54 mg GAE per g	*In vitro* antioxidant activities	A significantly higher amount of phenolic compounds with high antioxidant activities was observed	Osamede-Airouyuwa *et al.* (2022)[250]
Polyphenols	Seed	Methanolic–aqueous extraction	Phenolic acids	14.12 g kg^{-1}	*In vitro* digestion	The extracted polyphenols are bio-accessible, reach the colon as observed after digestion and are relatively unchanged for gut microbiota metabolism	Hilary *et al.* (2020)[251]
Polyphenols	Seed	Ethanol–aqueous	Phenolics	750 mg L^{-1}	*In vitro* anticancer, anti-hyperglycemic, antioxidant and anti-adipogenic activities	Significantly reduced viability in MCF-7 and Hep-G2 cells with 48 h treatments Glucose uptake increased in the adipocytes Inhibited adipocyte differentiation and lipid accumulation	Hilary *et al.* (2021)[173]
					Functional ingredients in bread	Retained antioxidant activity in the digestive milieu Increased phenolic contents and antioxidant activities after digestion of bread	
Polyphenols	Seeds	Aqueous Acetone (50%)	Phenolic Flavonoid	160.22 mg/100 g 193.83 mg/100 g	*In vitro* antioxidant activities	Date seed is an inexpensive source of phenolic compounds that can be used for antioxidant activities	Al-Farsi and Lee (2008)[53]
Polyphenols	Seed	Supercritical fluid CO_2 and subcritical CO_2 extraction	Phenolic acids	143.48–274.98 mg GAE/100 g	*In vitro* antioxidants	Innovative extraction of polyphenols from date seed improves their functional quality and antioxidant activities	Ghafoor *et al.* (2022)[153]
			Flavonoids	78.35–141.78 mg QE/100 g	Antiradical Reducing power		

Table 4 (*Contd.*)

Bioactive ingredients	By-product	Extraction method	Active ingredient	Yield	Functionality	Significant findings	Reference
Polyphenols	Seed	Hydrothermal extraction	Phenolic acids Flavonoids	1284.1 mg L^{-1}	Antiradical and oxygen radical absorbance capacity	Liquid fraction obtained after the application of a direct steam treatment at two temperatures allows the solubilization of a high quantity of phenolic compounds, making it possible to obtain an extract that is rich in phenols with high antioxidant activity	Mrabet *et al.* (2022)[252]
Polyphenols	Seeds	Dimethyl sulfoxide Aqueous Methanolic Formic acid		3541 mg/100 g 1694 mg/100 g 3284 mg/100 g	*In vitro* antioxidant activities	Iranian date seeds have significant antioxidant properties owing to their phenolic compounds; hence they could be sources of commercial and medicinal natural antioxidants	Shams Ardekani *et al.* (2010)[64]
Lignin	Seeds	Klason method with ethanol and benzene		26.68%	Additive for low-density polyethylene for wastewater treatment membrane preparation	Numerous hydroxyl groups in the extracted lignin cause improvement of the membrane hydrophilicity Decreased contact angle Increased membrane porosity	Zrelli *et al.* (2022)[253]
Polyphenols	Seeds	Ethanolic		8.521% GAE	*In vivo* hepatoprotective activities	The ethanol extract of date seed at doses of 150, 300, and 600 mg kg^{-1} had hepatoprotective activity in carrageenan-induced rats	Warsinah *et al.* (2022)[254]
Polyphenols	Seeds			3102–4430 mg GAE/100 g	*In vitro* antioxidant activities	Antioxidant activities are proportional to phenolic extracts	Al-Farsi *et al.* (2007)[79]
Polyphenols	Pomace			165–435 mg GAE/100 g	*In vitro* antioxidant activities	Antioxidant activities are proportional to phenolic content	Al-Farsi *et al.* (2007)[79]
Polyphenols	Seed	Methanolic extraction	Phenolic acids Flavonoids	2.194 g kg^{-1}		Date seeds are a very rich source of polyphenols and can be considered candidates for functional food and nutraceuticals	Habib *et al.* (2014)[65]

Table 4 (*Contd.*)

Bioactive ingredients	By-product	Extraction method	Active ingredient	Yield	Functionality	Significant findings	Reference
Polysaccharide	Seed	Aqueous and oxalate		1.9%	Radical scavenging potential, inhibition of glycation end product formation	PS *via* aqueous extraction gave maximum polysaccharide yield with molecular weight 1680 kDa, which had enhanced capabilities in scavenging free radicals, inhibiting glycation end products formation, and inhibiting lipid peroxidation	(Marzouk *et al.*, 2017)[16]
Polysaccharide	Seed	Hot water Ultrasound assisted	Water soluble PS	1.5% 1.03%	Antioxidant and radical scavenging potentials	Both extraction methods resulted in seed polysaccharides with excellent water solubility. Date seed PS takes the form of a heteropolysaccharide with excellent antioxidant and radical scavenging potentials	(Dhahri *et al.*, 2023)[207]
Polysaccharides	Seed	Ultrasound-assisted alkaline extraction		72%	*In vitro* antioxidant and antibacterial activity	Xylose was identified as the most abundant monosaccharide of PS. Polysaccharides displayed superior antibacterial and proliferative effects	(Noorbakhsh *et al.*, 2023)[203]

polysaccharides from various sources, which have evolved from traditional hot water extraction to the most recent green solvent extractions, offering a natural, economical, and least toxic approach towards efficient PS extraction (extraction, ultrasound, microwave, DES, *etc.*).

In the context of date fruit, PS constitutes the predominant bioactive component in both flesh and seeds, making up approximately 80% of their composition. Bendahou *et al.* (2007)[200–202] have documented the extraction of polysaccharides from date palm and its parts. Date flesh is reported to have around 14% polysaccharide, characterized by (1→3)-β-D-glucopyranosyl residues branched saccharide residues at (1→6). Detailed characterization studies have revealed the presence of xylans, primary hemicellulose polymers in date seeds, consisting of β-1,4-linked D-xylose with side chains of L-arabinose, D-galactose, and acetyl groups.[203] Libyan date seeds, as a possible valuable source of glucomannan (a neutral polysaccharide consisting of mannose, glucose, arabinose, and rhamnose) and arabinogalactan (an acidic polysaccharide of MW 48000 made of arabinose, galactose, rhamnose, and glucose), were reported by Ishurd *et al.* (2003).[204] β-D Glucans present in date flesh were observed to have a linear structure composed of a combination of (1→3)- and (1→4)-linkages.[205] The glucans in dates exist as two major fractions of different molecular masses: fraction I with Mtw 200 000 and fraction II with Mtw 10 000. These fractions exhibit variations owing to the inclusion of (1/6)-branched chains made up of D-glucose units, with the lowest molecular weight polysaccharide containing Glcp-(1/3)-D-Glcp groups and the highest molecular weight polysaccharide consisting of D-Glcp-(1/3)-D-Glcp units.[206] Identification of an alkali-soluble heteroxylan from date seeds, composed of D-xylose and 4-*O*-methyl-D-glucuronic acid, was reported by Ishurd *et al.* (2003).[204] The polysaccharide was reported to have the structure of an aldobiouronic acid from hemicellulose, which exists as a polymer of (1→4)-linked D-xylopranosyl residues with branched D-xylopyranosyl and 4-*O*-methyl-α-D-glucopyranosyluronic acid.

Water-soluble PSs were extracted from Ajwa date seeds by Dhahri *et al.* (2023),[207] and the seed variety is known for its antioxidant, antimicrobial, anticancer, and antiviral properties. Two different extraction methods were employed to compare the yield of the extracted PS. Both hot water and ultrasound-assisted extractions resulted in seed polysaccharide yields of 1.5% and 1.03%, respectively, with excellent water solubility. Date seed PSs are structurally like heteropolysaccharides with excellent antioxidant and radical scavenging potentials. Noorbakhsh and Khorasgani (2023)[203] employed ultrasound-assisted alkaline extraction of date seed polysaccharides from the Zahidi date variety. Xylose was identified as the most abundant monosaccharide from the extracted polysaccharide, contributing to approximately 72%. The polysaccharide displayed superior antibacterial and proliferative effects compared to standard PS and date flesh polysaccharides. Seed polysaccharides showed positive regulation of gut microbiota because of their prebiotic potential, influenced by their monosaccharide composition, molecular weight, and extraction method.[197] *In vitro* digestion studies of date seed PS confirmed their prebiotic potential, as the polysaccharide was stable in the upper digestive tract and later reached the colon to be metabolized by the gut microflora. Intervention and blood biomarker analysis of the polysaccharide indicate its efficiency in reducing serum C-reactive protein (reducing inflammation by supporting the growth of beneficial gut microflora), reducing triglycerides, fasting blood sugar (hypoglycemic effect), and increasing red blood cells (antioxidative effect of the polysaccharide). Marzouk *et al.* (2017)[16] employed aqueous and oxalate extraction of date seeds to yield PS, out of which the former method yielded the maximum, *i.e.*, 1.9% polysaccharide with a molecular weight of 1680 kDa. Water-extracted PS exhibited enhanced capabilities in scavenging free radicals, inhibiting glycation end product formation, and inhibiting lipid peroxidation and protein glycation.

4.3 Melanin

Melanin, a naturally occurring complex secondary metabolite found extensively in animals, plants, fungi, and bacteria, has been substantiated through both *in vivo* and *in vitro* examinations to possess diverse health-enhancing properties, such as antioxidative, anti-inflammatory, radioprotective, gastrointestinal, immunomodulatory, hypoglycemic, and anti-hyperlipidemia effects alongside safeguarding internal organs.[208–212] Recent studies have revealed that melanin derived from natural sources exhibits heightened antioxidant efficacy attributed to its ability to scavenge reactive oxygen species (ROS).[211] Naturally occurring melanin is made of complex heterogeneous polymers and can be broadly categorized into five groups based on their structural characteristics: eumelanin, pheomelanin, neuromelanin, allomelanin, and pyomelanin.[213] Allomelanin is the form of melanin present in date fruits (Alam *et al.* (2022)),[214] which showed excellent radical scavenging activities explained by DPPH and ABTS IC50 values of 63.6 to 75.1 μg mL^{-1}, respectively, and potential hypoglycemic effects.

Green extraction of melanin is quite challenging because of the localized presence of melanin in melanosomes where they are found closely bound to the inner cell wall or the cellular components.[215] Elobeid *et al.* (2017)[209] posited that the enzyme tyrosinase facilitates the synthesis of melanin *via* enzymatic action on the amino acid tyrosine. Initially, tyrosine undergoes hydroxylation and is converted to catecholamine 3,4-dihydroxyphenylalanine, which is subsequently oxidized to 3,4-dioxyphenylalanine or dopaquinone. In later stages, dopaquinone is cyclized to form 5,6-indole quinones, the polymerization of which leads to the formation of melanin. An elevated concentration of melanin pigments was observed in the date fruits. In date fruits, Al-Amrani *et al.* (2020)[216] identified that the onset of enzymatic browning is triggered by the activity of the enzyme polyphenol oxidase, which interacts with phenolic compounds in the presence of oxygen, leading to a brown compound, *O*-quinones. *O*-Quinones undergo a nonenzymatic polymerization process, resulting in the formation of diverse dark polymers referred to as melanin. In date fruits, approximately 0.0859% of melanin is extracted *via* chemical treatment using sodium hydroxide.

The brown coloration of melanin in date fruits remains consistent, even in dark varieties such as Ajwa and Safawi, indicating a possible coexistence of melanin and proanthocyanidins in these fruits. Additionally, condensed tannins polymerized with epicatechin have been reported in Tunisian Deglet Nour date varieties.[214] Interestingly, Huang *et al.* (2020)[217] reported results about date seed extracts. Unlike date fruits that contained melanin, the seed extracts prevented melanogenesis because of their capability to scavenge reactive oxygen species. Seed extract prevented the inhibitions of the melanocortin 1 receptor, associated transcription factor, tyrosinase, and related protein 1, thereby preventing the onset of melanogenesis in treated cells. This, however, has not been implemented in food systems because it requires extensive clinical trials.

4.4 Lignin

Accumulated evidence from epidemiological data reveals a moderate but significant positive correlation between fruit and vegetable consumption and a reduced risk of mortality and chronic metabolic diseases, such as cancers, obesity, and cardiovascular diseases.[176,218] Fruit and vegetable consumption generally improves diet components owing to their richness in micro and macronutrients, including dietary fibers (DF), which provide potential health benefits, such as anti-inflammatory, anticancer, fecal bulkiness, antioxidants, and the production of short-chain fatty acids, in the body.[219,220] DFs consist of cellulosic, non-cellulosic, and non-polysaccharide lignin.[221] Interestingly, date fruits contain about 6.5–11.5% of DF, with 6–16% of soluble and 84–94% of insoluble fractions. Hemicellulose, lignin, and cellulose are insoluble DF, which improve gut health.[222,223] The date palm biomass was reported to consist of 26.4% lignin, 14.8% cellulose, and 30.2% hemicellulose.[224]

Importantly, among the insoluble DF, lignin has antioxidant properties. Lignin is a complex phytocompound existing between cellulose and hemicellulose, which is widely distributed in the date flesh and synthesized from about 40 monomers, mainly oxygenated phenyl propane (coniferyl, sinapyl, and *p*-coumaryl alcohols).[92,225] Lignin is the second most abundant phytometabolite after cellulose with the potential to produce valuable bioactive compounds,[226,227] making lignin an important natural compound with various applications in energy, food, pharmaceuticals, cosmetics, and materials development industries.[228]

Analytical studies by Hamada *et al.* (2002)[61] revealed that date seeds contain about 65–69% neutral detergent fiber (mannose, rhamnose, glucose, and arabinose), which positively correlates with the presence of a remarkable quantity of lignin.[155] A comparative study on different varieties of Tunisian dates also confirmed a range of 19.6–25.4% of lignin present in the date seeds.[222] Unlike polyphenols and other bioactive compounds, research into the lignin component and the application of date by-products is still novel and emerging, requiring much attention from the scientific community. Further studies are needed to explore the valorization of this important bioactive compound.

5. Conclusions and future directions

This review delves into date seeds and pomaces as major by-products of date palm processing industries, with a special focus on their techno-functional and bioactive properties, aimed at efficient valorization as food ingredients. Date seeds and pomace, with their secondary metabolites, have demonstrated antioxidant, antimicrobial, anti-inflammatory, anticancer, reduced cytotoxic, health-promoting prebiotic, and probiotic functionalities. These properties make them a cost-effective alternative, suitable for utilization as functional food ingredients, effectively transforming waste products into economically viable food substrates.

To comprehend the intricate biochemical changes occurring in the food matrix upon the addition of date by-products as functional ingredients, further investigations employing suitable animal models need to be conducted. Additionally, there is a noteworthy research gap concerning the extraction of polysaccharides and melanin from date pomace. Despite the available data, limited *in vitro* and *in vivo* exploration of these bioactive-rich components in terms of their health-promoting potential exists, which is crucial for the commercialization of value-added products derived from them.

The strategic utilization of biological wastes like date seeds and pomace, for the extraction of bioactive compounds aligns with sustainable production and utilization practices, fostering the principles of a circular economy. The bioactive components of both seeds and pomace hold significant potential for applications in the food industry. This review asserts that the industrial wealth, particularly seeds and pomace from date processing industries, offers a promising alternative to artificial sources relied upon for the same purpose. Not only does it circumvent potential health and safety hazards associated with artificial additives, but it also helps mitigate the risk of various diseases.

Author contribution

A. Subhash: writing – original Draft. G. Bamigbade: writing – original draft. M. Ayyash: conceptualization, writing – review & editing, supervision.

Conflicts of interest

The authors declare no conflict of interest.

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