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Review

Valorization of Date Fruit (*Phoenix dactylifera* L.) Processing Waste and By-Products: A Review

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Abstract: The date is a well-established and important crop that holds economic significance. However, a substantial amount of waste in the form of low-grade dates and date pits is generated and accounts for 10 to 15% of the total production. Given the substantial amount of nutrients in these by-products and the large volume of waste generated, there is a promising opportunity to utilize them to create valuable commodities like fiber and phenolic compounds, which hold a high market value. This review presents a summary of the chemical and nutritional composition of dates and their by-products and aims to investigate the possibility of utilizing date processing by-products and waste as an eco-friendly resource for various chemical and biological processes like composting and extraction of value-added compounds, as well as providing insight into the date processing industry and typical methods employed for the beneficial use of date waste. In addition, this review also addresses the current challenges and future perspectives in date waste valorization expectations.

Keywords: date palm; processing waste; valorization; nutritional and biochemical composition; high-value compounds

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1. Introduction

Date palm (*Phoenix dactylifera* L.) is an important agricultural crop that has been widely cultivated across the globe. Currently, over a thousand varieties of date palms have been recognized worldwide including highly acclaimed varieties like Ajwa, Medjool, Khalas, Deglet Noor, and others [1]. Dates have primarily been cultivated in dry and semi-dry regions for more than five millennia [2]. The global production of date palms has steadily increased over the past decade, indicating a growing demand for this fruit (Figure 1). Currently, the majority of dates are produced in the Middle East and North Africa, accounting for 90% of worldwide output [3].

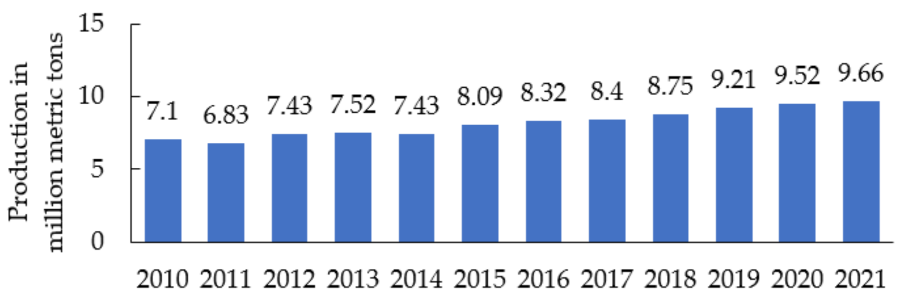


Figure 1. Global production of date palm from 2010 to 2021 [4].

The date fruit processing industry plays an increasingly important role in the agro-industrial sector, as these fruits can be transformed into a variety of products, such as date syrup, alcohol, date powder, and paste [5]. Apart from the fruit pulp, other date palm components can also substantially contribute to the agricultural economy. For instance, the date palm stem can be utilized for various purposes such as, for example, to produce boats, roofing, paper, and fiber [6]. Furthermore, local handicrafts such as nets and mats can be created from date foliage [7].

In addition, date fruits provide an economical and abundant supply of vital nutrients, including carbohydrates like soluble sugars and fiber, minerals, and vitamins [2,8]. The date fruit also has minimal quantities of fats and proteins. Furthermore, date fruits, including their pulp and seeds, encompass significant nutraceutical elements (such as phenolic compounds, phenolic acids, cinnamic acid derivatives, flavones, anthocyanidins, isoflavones, and volatile compounds) that deliver practical benefits [9]. These benefits encompass antioxidant, antimicrobial, anti-inflammatory, antimutagenic, hepato-protective, gastro-protective, anticancer, and immune-stimulating properties [2,10,11]. Habib et al. [12] explored the health benefits of date palm fruit seed extract and its mechanism of action. Their study reveals that the extract inhibits free radicals, labile iron activities, and DNA/protein damage, suggesting its potential to protect against oxidative damage and programmed cell death due to iron-catalyzed ferroptosis. Additionally, date palm fruit seed extract inhibits enzymes linked to various diseases. These findings support the use of date palm fruit seed extract in functional foods and nutraceuticals, encouraging further in vivo and clinical trials.

A considerable quantity of waste is produced during the processing of date fruit, including the date pits and the date press cake (produced during date juice extraction). Date pits represent an average reduction of 10% in the weight of the whole fruit [13]. Even though date palm agricultural wastes contain valuable components such as dietary fibers, phenolic compounds, and other bioactive compounds, they are often discarded or used inefficiently [14,15].

While many researchers have explored date palm cultivation, its potential uses, and applications in therapy, there is limited availability of comprehensive reviews in the literature that extends beyond the chemistry and pharmacology of date fruits. Therefore, in this review, we explore the potential of utilizing bioprocessing technologies to maximize the value of date fruit processing by-products and waste materials, aiming for the complete utilization of these waste products that are typically disposed of into the environment. This comprehensive review covers various aspects, including the nutritional value and biochemical characteristics of date fruits, their medicinal and pharmacological properties, date fruit processing and the generation of products and by-products, current waste management practices, and challenges and opportunities for enhancing value through bioprocessing, the production of fermented products from date palm fruits, and a brief discussion of future trends in the valorization of date palm fruit processing by-products and waste materials.

2. Types of Date Palm Waste

The process of harvesting date palm fruit typically results in substantial losses due to fruit falling from the tree prematurely and issues during storage and conditioning. These lost dates are commonly referred to as “date by-products” and are considered of low grade due to their inadequate texture, being either too hard or too soft and being contaminated with fungi or infested by insects. Owing to these quality problems and safety risks, these lost dates were generally discarded in the past [16]. Currently, these by-products can be used as animal feed compost, among other purposes, thereby enhancing their value to a certain extent [17].

The processing of pitted dates generates two major types of waste: the whole date fruits that do not meet quality requirements, and the seeds that are removed during the production process. The seed waste generated from the pitting process of date fruit makes up about 18% of the fruit’s total weight [18] (Figure 2). Considering that the world production of dates reached 9.66 million tons in 2021, this would potentially generate over 900,000 tons of date seeds [4]. Indeed, date seeds, previously considered waste, have now gained recognition as a valuable source of fiber and phenolic compounds. Furthermore, they can be converted into products that have added value. Moreover, the oil extracted from date seeds can be converted into value-added products.

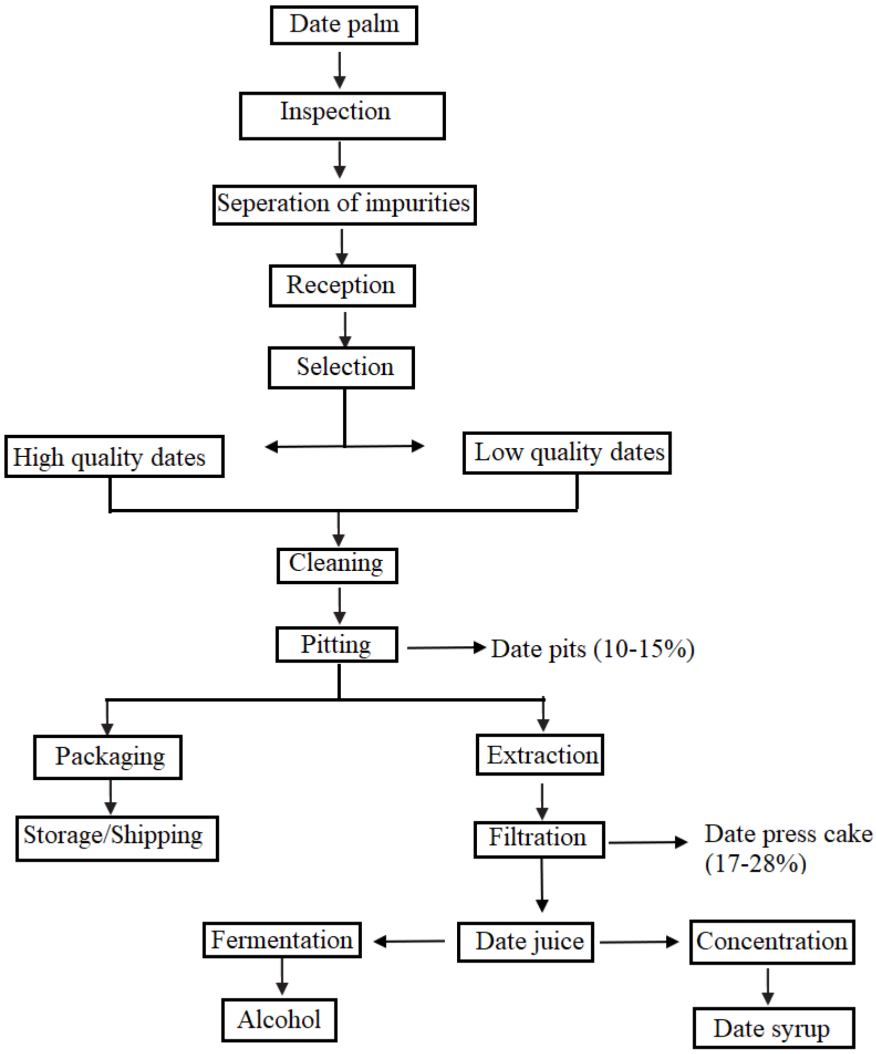


Figure 2. Flowchart of pitted date processing and date juice processing.

Date seed oil (DSO) can be extracted from date seeds using different methods, including Soxhlet extraction, hydrothermal and ultrasonic-assisted methods, and supercritical and subcritical CO_2 techniques [10,19]. DSO has numerous applications in the food industry, including its use in cooking, frying, and seasoning. DSO can be used as a replacement for palm olein, a common ingredient in many food products [20]. Previous reports have also mentioned that DSO has been used in margarine production and as an alternative to vegetable oils like corn and sunflower oil in mayonnaise production [19]. DSO can also be used in cosmetic formulations such as body creams, shaving soap, and shampoo [21]. Research has revealed that DSO has properties that help reduce cellular and oxidative rancidity, and it can protect human skin from UV irradiation, making it beneficial for skincare and cosmetic products [21]. In addition, DSO can be utilized in other non-food applications, such as biogas production of deoxygenated hydrocarbons, where DSO can serve as a substrate [22]. DSO's potential applications in both food and non-food industries highlight its versatility and potential value as a by-product of date processing.

Low-grade dates, unsuitable for direct consumption, can be used to produce other products such as date paste and date juice. Date juice can be further processed to produce date spread, syrup, and liquid sugar or fermented to produce wine, alcohol, and vinegar. Date juice production typically produces date press cake (DPC), a fibrous by-product that remains after the filtration of date juice (Figure 2). This by-product is often bulky in nature and has a high content of moisture and carbohydrates [23]. Date juicing can produce about 17–28% of DPC with high nutritional value, although the conventional use of DPC is still for animal feed or directly discarded [17].

3. Nutritional and Biochemical Composition of Date Fruit and Date By-Products

Date palms contain abundant essential macro- and micro-nutrients, including carbohydrates, fatty acids, protein, amino acids, minerals and salts, vitamins, and dietary fiber. These compounds can be powerful substances found in dates and date wastes that have the potential to positively influence health. Functional ingredients and dietary supplements could be generated by employing various methods to identify and separate these compounds from date waste. This approach could reduce waste and promote sustainability in the date palm industry (Figure 3).

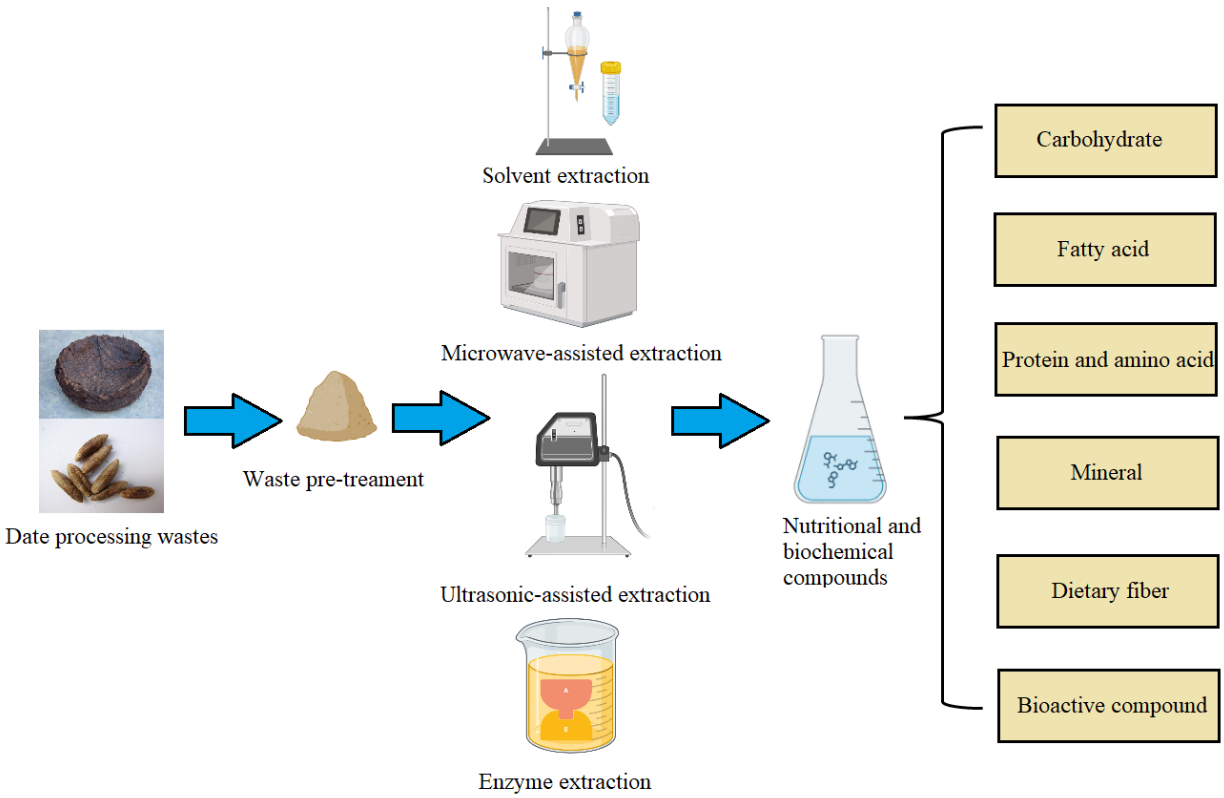


Figure 3. Extraction of nutritional and biochemical substances from date waste using various extraction methods.

The proximate nutritional composition of date fruit and date pit is shown in Table 1. Dates at fresh edible stages may have a moisture content of around 40%, and the high nutritional value of dates is due to their high content of sugar, potassium, calcium, magnesium, and iron as well as vitamins (B1 and B2) and niacin [2,24,25]. Date seed contains 8–12% moisture, 60–80% fiber, 4–14% fat, and 5–7% protein. The date seed also contains various phytochemicals, including tannins, flavonoids, terpenoids, saponin, anthraquinone, and alkaloids, as well as essential minerals like potassium and calcium [26]. Date seed fiber contains both soluble and insoluble dietary fibers, and the content of dietary fiber content in seeds is proven to be higher than date pulp [27]. The main components of insoluble fiber are hemicellulose, cellulose, and lignin [21]. Attia et al. [27] reported that the high fiber content in date seeds can substitute corn and barley in the diet. Date seeds contain different fiber fractions, including acid detergent fiber, neutral detergent fiber, hemicellulose, cellulose, and lignin. Acid detergent fiber is a combination of cellulose and lignin, ranging from 39.6% to 57.5% [26]. Neutral detergent fiber is a combination of hemicellulose, cellulose, and lignin and ranges from 51.6% to 75.0% [26]. Hemicellulose content in date seeds ranges from 12.0% to 17.5%, while cellulose ranges from 26.1% to 42.5%. Additionally, lignin content in date seeds falls within the range of 7.21% to 11.0% [26].

The proximate nutritional composition of DPC is also shown in Table 1. Majzoobi et al. [23] also found that magnesium is the mineral with the highest content in DPC, which has an average of 959.5 mg/kg, followed by phosphorus (853.4 mg/kg) and calcium (460.5 mg/kg). Surprisingly, DPC has an average phenolic content value of 17.8 mg/g, which is very close to fresh date fruit (18 mg/g), which showed that high antioxidant compounds remain in DPC after date juice extraction [23]. The composition of DPC was found to vary, with crude protein ranging from 4.1% to 10.5%, neutral detergent fiber at 48%, acid detergent fiber at 25.6%, and nitrogen-free extract at 40.1% [28]. Due to its high fiber and antioxidant content, the DPC left over from processing dates can be useful as an ingredient in healthy foods. The natural brown color of DPC makes it a good option for darker foods like baked goods, and its ability to hold onto the water is an advantage in products like salad dressings and instant soups [23]. The particle size of DPC is also important to consider, as it can affect its chemical composition, nutritional value, and usefulness in different foods [23].

Table 1. The proximate nutritional composition of date fruit, pit, and date press cake.

Component	Date Fruit (per 100 g)	Date Pit (per 100 g)	Date Press Cake (per 100 g)	References
Moisture (g)	12.60–50.40	1.42–4.14	6.11–13.4	[18,23,29–31]
Carbohydrate (g)	76.69–90.18	83.39–85.55	66.2–79.1	[18,23,31]
Protein (g)	1.60–3.53	3.20–5.00	4.10–10.5	[18,23,31]
Fat (g)	0.32–1.09	6.30–7.40	4.92–5.12	[18,23,31]
Ash (g)	2.08–2.50	1.14–1.50	2.78	[18,31]
Dietary fiber (g)	8.10–12.70	64.50–79.84	11.7–12.4	[23,29,31,32]
Calcium (mg)	15.46–53.82	28.9–38.8	41.74–50.35	[21–23]
Phosphorus (mg)	52.19–77.94	83.6–68.3	54.17–116.51	[21–23]
Sodium (mg)	6.25–17.52	10.25–10.4	0.16–0.25	[21–23]
Potassium (mg)	281.74–478.29	229–293	54.17–116.51	[21–23]
Magnesium (mg)	42.17–70.38	51.7–58.4	82.57–109.33	[21–23]
Iron (mg)	0.84–1.51	2.30–2.21	7.14–9.01	[21–23]

3.1. Carbohydrate

The sugar composition of dates varies depending on the species and the maturity stage of the fruit. Typically, the date palm reaches its highest sugar concentration at its mature (Tamar) stage [29]. Most date cultivars contain glucose, fructose, and sucrose, which are easily absorbed by the body to provide energy. In fresh dates, the concentration of inverted sugars is higher than in semi-dried dates. In semi-dried dates, the ratio of inverted sugars to sucrose is similar, while in dried dates, the concentration of sucrose is higher than that of inverted sugars [33]. The overall sugar content in dates consists of both reducing and non-reducing sugars, and these proportions vary noticeably across different types of dates. The total sugar levels in various date cultivars ranged from 59.0% to 73.9% (dry weight basis). Among these cultivars, the reducing sugars concentration ranged from 52.8% to 69.0%, while the quantity of non-reducing sugars fell between 4.65% and 7.66% [34].

3.2. Fatty Acids

Fatty acids play a crucial role in various physiological functions in the human body, including energy storage, cell membrane structure, and signaling [35]. The fatty acid composition of the date palm varies depending on the cultivar, geographic location, and maturity stage of the fruit [36]. The major fatty acids present in the date palm include palmitic acid (C16:0), oleic acid (C18:1), linoleic acid (C18:2), and stearic acid (C18:0) [37].

Palmitic acid is a saturated fatty acid accounting for around 10–15% of the total fatty acid content in date palm fruit [37]. Palmitic acid has been associated with an increased risk of cardiovascular disease and insulin resistance when consumed in excess. However, moderate consumption of palmitic acid from natural sources such as date palm fruit may not have negative health effects [38]. Stearic acid is another saturated fatty acid that accounts for around 5–10% of the total fatty acid content in date palm fruit [39]. The consumption of high amounts of saturated fatty acids is related to high LDL cholesterol levels in the blood, raising the risk of heart disease and stroke [40].

Oleic acid is a monounsaturated fatty acid that accounts for around 40–50% of the total fatty acid content in date palm fruit, which is the highest among all of the fatty acids, and linoleic acid is a polyunsaturated fatty acid that accounts for around 8–19% [37]. Unsaturated acids can improve heart health by lowering LDL cholesterol levels and enhancing insulin sensitivity [41]. Oleic acid is also involved in synthesizing various hormones and cell membrane structures [42]. Furthermore, date seed oil, rich in linoleic acid, has skin-enhancing and protective properties due to its essential fatty acids that our body cannot produce naturally. Insufficient levels of these essential fatty acids can lead to skin issues such as dryness, flakiness, fragile nails, and hair thinning. Numerous skincare products utilize linoleic acid to address conditions like acne vulgaris, skin disorders, and sunburn [29].

3.3. Protein and Amino Acids

Proteins are large organic molecules with one or multiple lengthy sequences of amino acids. Traditionally, individuals have obtained protein by consuming animal-based sources such as meat, eggs, and milk. However, the research on alternative protein sources to replace expensive animal proteins has led researchers to consider materials previously considered wastes but rich in protein. While the protein content of date palm may not be as high as its carbohydrate content, its essential amino acids provide significant benefits to human health [29]. Recovering functional proteins from date waste can increase the value of discarded low-grade fruits and date peels, skins, and seeds.

Date fruits have a protein range of 2.43% to 3.12%, while protein content in date seed is 4.81% to 5.84 [21,43]. Rambabu et al. [43] reported the presence of essential amino acids in dates, with significant proportions of glutamine, aspartic acid, glycine, proline, histidine, and valine. In their research, it was observed that all tested date varieties predominantly contained glutamine and aspartic amino acids, with varying percentages ranging from 24.23% to 38.82% for glutamine and 20.98% to 32.11% for aspartic acid. Additionally, glycine, proline, histidine, and valine were also present in notable amounts, contributing to the overall amino acid composition of dates, with concentrations ranging from 11.60% to 18.03%, 9.83% to 14.19%, 3.47% to 6.20%, and 8.23% to 12.02%, respectively. Other essential amino acids, such as glycine, proline, and valine, were also at significant levels. These amino acids play a crucial role in the formation and synthesis of proteins in the body, involving the production of neurotransmitters or the formation of collagen, as the protein is the structure that forms the connective tissues in the body, including cartilage, tendons, and ligaments [44]. Also, the isoleucine content in dates is over 800 times greater than that found in apples [45]. According to the research conducted by El-Dreny and Shaheen [46], the quantity of lysine found in dates is remarkably high. Specifically, the lysine content in date seeds, at 4.05 g per 100 g of protein, is higher than the lysine in wheat flour by approximately 1.8 times, which is 2.46 g per 100 g of protein.

3.4. Minerals

Minerals are significant constituents of the date palm, and their content plays a vital role in evaluating the nutritional quality of dates. Tripler et al. [47] reported that there are at least 15 essential minerals in date palms, including phosphorus, potassium, sodium, zinc, manganese, magnesium, copper, and iron. Minerals play an essential role in the human body, including building strong bones, transmitting nerve impulses, regulating the stability of human hormones, and regulating the standard heartbeat.

Rambabu et al. [43] evaluated 11 date fruit cultivars and found that potassium was the major mineral element present in all date varieties, ranging from 281.7 to 478.3 mg/100 g. Iron was present in good levels in all date varieties, with a maximum of 1.51 mg/100 g in Raziz date flesh. The mineral content may vary among different cultivars of dates due to other factors such as variety, soil type, and amount of fertilizer [48]. However, for individuals diagnosed with hypertension, a dietary regimen supplying lower sodium intake while increasing potassium intake in their diet may assist in lowering blood pressure level. The use of date palm by-products with high potassium and low sodium content presents an opportunity in the field of medicine for the treatment of high blood pressure [49].

3.5. Dietary Fibers

The date palm is a valuable source of dietary fiber, and a significant portion of that fiber can be found in the flesh of the fruit [37]. Date palm dietary fiber contains soluble and insoluble fibers, whereas both have different physiological effects on the body. Soluble fibers such as pectin and hemicellulose can be dissolved in water and form a gel-like substance in the digestive tract [50]. Besides that, soluble fibers can regulate blood sugar levels by inhibiting the rapid digestion and absorption of carbohydrates and lipids, lowering cholesterol levels, and promoting the growth of healthy gut bacteria [51]. Insoluble fibers such as cellulose and lignin can add bulk to fecal matter and maintain and promote bowel movement, which can help prevent constipation and other digestive disorders [51].

The main dietary fiber compounds in date palms include cellulose, hemicellulose, pectin, and lignin. Cellulose is a linear polymer of glucose units that forms the structural component of plant cell walls, and its content in date palm can be over 30 g/100 g [52]. Hemicellulose is a branched polymer composed of several sugars, including xylose, arabinose, and galactose. Dates contain a significant amount of hemicellulose, ranging from approximately 24.0% to 45.1% of their overall composition [52]. The date also has a high value of pectin, which is a non-cellulosic fiber. However, the pectin amount varies widely with ripening stages of the date fruit because the process involves increased activity of fiber-hydrolyzing enzymes (pectinase). High-quality dates generally have elevated pectin and low lignin, whereas the opposite pattern results in less palatable to inedible fruit [24]. The pectin content in date palm can range from 0.78 to 1.12% [53]. Lignin is a complex phenolic polymer that gives plant cell walls rigidity and resistance to degradation, ranging from 22 to 23% in dates [54].

Recent studies indicate that fibers from date palms have prebiotic properties, which can aid in the growth of beneficial gut bacteria. Bamigbade et al. [55] reported that date palm fibers increased the abundance of beneficial bacteria, such as *Bifidobacterium* and *Lactobacillus*. Another study showed that date palm fibers can reduce inflammation in the human body, which may benefit those with inflammatory bowel diseases [26]. The considerable amount of dietary fiber in dates may be beneficial for individuals with diabetes by the regulation of blood sugar levels. Alkaabi et al. [56] studied the impact of date consumption on blood sugar levels in healthy individuals and those with type 2 diabetes mellitus. The findings indicated that the five types of dates examined in the study have a low glycemic index and did not cause significant increases in postprandial glucose levels when consumed by diabetic individuals. Therefore, including dates in a balanced and healthy diet may offer benefits for individuals with diabetes. This explanation was also supported by Goff et al. [57], who suggested that a diet rich in dietary fiber may aid in balancing blood sugar levels, likely owing to the presence of fiber and bioactive compounds in dates, which can slow down the absorption of glucose from a meal.

3.6. Bioactive Compounds—Phenolic Compounds and Antioxidant Activity

The date fruit is a rich source of phenolic compounds that possess biological activity due to the presence of a benzene hydroxyl ring with a carboxyl group [58]. The date fruit contains a range of phenolic compounds, including phenolic acids, flavonoids, and high-molecular-weight compact polymers [3,36]. There are four primary categories of phenolic compounds found in plants, namely phenolic acids, flavonoids, stilbene, and lignin. They can be categorized based on their dissimilarities in structure, the number of phenol rings, and the type of molecular linkage [59].

The polyphenols exhibit their antioxidant properties by eliminating free radicals and reactive oxygen species, thereby inhibiting the oxidative process, which may help prevent diseases associated with oxidative stress, and improving glycemic control, lowering blood pressure, and improving lipid profiles [27]. Phenolic acids and flavonoids are the main polyphenols present in the fruit pulp and seeds, and due to the higher concentration of phenolic compounds in the seeds, the antioxidant capacity of the seeds is often greater than that of the pulp. Hilary et al. [60] analyzed polyphenols in Khalas date seeds in three human-consumable forms: date seed powder, date seed pita bread, and date seed extract and identified 27, 29, and 15 compounds via HPLC-ESI-UV/MS/MS and confirmed by UPLC-QTOF MS/MS, respectively. These compounds included hydroxycinnamic acids, hydroxybenzoic acids, hydroxyphenyl acetic acid, flavanols, flavonols, and flavones. Flavan-3-ols were the most abundant polyphenols. The study revealed that polymeric proanthocyanidins are present in date seeds and can potentially undergo gut microbial metabolism. During the process of in vitro digestion, there was an increase in the number of polyphenols present in the intestinal phase, indicating a favorable level of bioaccessibility. Several key phenolic acids and flavones were actively transported across Caco-2 monolayers, suggesting significant bioavailability from date seeds, while some procyanidins remained undetected in transport, possibly due to their binding to carbohydrates and protein precipitation properties. Several studies have evaluated the antioxidant activity of date palm, and some of these studies are listed in Table 2. However, it is worth noting that the content of phenolic compounds in dates can differ based on the variety of dates.

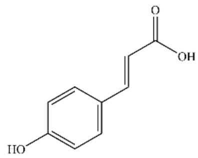
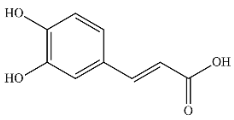
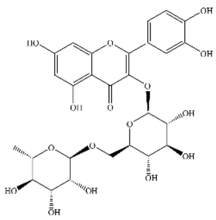
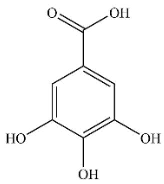
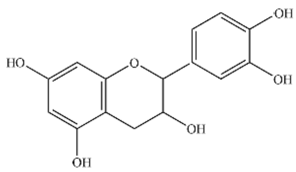
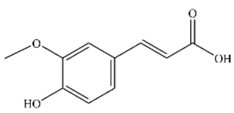
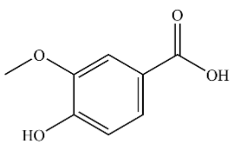
Table 2. Studies on the phenolic compounds and antioxidant properties of date fruits.

Date Varieties	Method(s)	Findings	Reference
Ajwah, Safawy, and Sukkari (Saudi Arabia)	Antioxidant activity by DPPH, hydroxyl radical scavenging and total antioxidant capacity assay. The qualitative phenolic composition was determined using UPLC-QTOF-MS.	The extracts showed DPPH radical scavenging (IC_{50} 103–177 µg/mL) and hydroxyl radical scavenging (IC_{50} 1.1–1.55 mg/mL) activity and total antioxidant capacity (IC_{50} 87–192 µg/mL). UPLC-QTOF-MS revealed a total of 22 compounds in these date cultivars classified into common phenolics, flavonoids, sterols, and phytoestrogens.	[61]
13 varieties from UAE; 10 varieties from Pakistan; 1 variety from Tunisia	Total phenolic content and antioxidant activity using the Folin–Ciocalteu, $ABTS^+$, FRAP, and DPPH assays.	The total phenolic content varied 46–397 mg GAE/100 g fresh weight (FW) using the Folin–Ciocalteu method, 0.9–4.3 µmol TE/100 g FW using $ABTS^+$, 355–2421 µmol TE/100 g FW using FRAP, and 0.0–1.8 mg/mL using DPPH.	[62]
Medjool (Mexico)	Total phenolic content by the Folin–Ciocalteu method, antioxidant activity by DPPH, ABTS, and β-carotene assay.	Total contents of phenolic compounds (pulp: 1.16 mg of GAE/100 g; seeds: 13.73 mg of GAE/100 g) and antioxidant activity (β-carotene, 65.50% and 47.75%; DPPH, 0.079 IC_{50} g/L and 0.0046 IC_{50} g/L; and ABTS, 13.72 IC_{50} g/L and 0.238 IC_{50} g/L).	[13]
19 varieties from Pakistan	Total phenolic content by the Folin–Ciocalteu method. The qualitative phenolic composition was determined using HPLC.	The range of the total phenolic contents ranged from 142.52 $\pm$ 0.64 to 298.02 $\pm$ 0.95 mg GAE/100 g on fresh fruit weight basis. Seven phenols of chlorogenic acid, caffeic acid, vanillic acid, gallic acid, cinnamic acid, 3,5-DHB, and 2,5-DHB were identified and quantified in four varieties of date seeds.	[34]
Kabkab, Rabbi, Zahedi, and Mazafat (Iran)	Total phenolic content by the Folin–Ciocalteu method and phenolic compound identification and quantification by HPLC analysis.	The phenolic contents for the date pit extracts ranged 1483–3377 mg GAE/100 g dw.	[63]

GAE, gallic acid equivalents; TE, Trolox equivalents.

Compared with date fruit, date seed has a relatively higher content of antioxidant compounds, especially phenolic compounds. In addition, date seeds have a high level of total polyphenol content compared to other fruits such as grapes and other types of seeds like nut seeds. The high polyphenol content in date seed has been proven to possess a variety of pharmacological effects, including anti-inflammatory, anticancer, and antimutagenic activities [26,64]. Current studies show that date seeds contain phenolic acids such as caffeic, chlorogenic, *p*-coumaric, ferulic, gallic, syringic, and vanillic acid [65]. Some of the important phenolic compounds that can be isolated from date pits are listed in Table 3.

Table 3. Important phenolic compounds isolated from date pits.

Compound Name	Classification	Structure	Molecular Formula	Extraction and Identification Method	References
p-coumaric acid	Hydroxycinnamic acid		$C_6H_4(OH)COOH$	Solvent extraction; Ultrasonic bath extraction; HPLC	[65,66]
Caffeic acid	Hydroxycinnamic acid		$C_9H_8O_4$	Solvent extraction; HPLC	[65]
Rutin	Flavonoid glycoside		$C_{27}H_{30}O_{16}$	Solvent extraction; HPLC; LC-MS	[65,67]
Gallic acid	Phenolic acid		$C_6H_2(OH)_3COOH$	Solvent extraction; HPLC	[65]
Catechin/epiccatechin	Flavan-3-ol		$C_{15}H_{14}O_6$	Ultrasonic-assisted extraction; HPLC	[68]
Ferulic acid	Hydroxycinnamic acid		$C_6H_8O_4$	Solvent extraction; HPLC; LC-MS	[65,67]
Vanillic acid	Benzoic acid derivative		$C_8H_8O_4$	Solvent extraction; HPLC	[65]

Iranian date seeds were previously reported to have high antioxidant activity, with 37.42 mmol Fe^{II}/100 g, showing a potential to be applied in medicinal and commercial areas. Also, the phenolic content of Iranian date seeds reached a high content of 3541 mg gallic acid/100 g dry plant [69]. The Mabseeli variety of date seeds has a substantial concentration of phenolic compounds, including gallic acid, protocatechuic acid, *p*-hydroxybenzoic acid, vanillic acid, caffeic acid, *p*-coumaric acid, ferulic acid, *m*-coumaric acid, and *o*-coumaric acid. These compounds have been identified in this particular type of date seed [70]. Alshwyeh [67] analyzed three varieties of dates, Ajwa, Khalas Alkharj, and Al-Qasim, using LC-MS and LC-MS/MS, and a large group of unique phenolic compounds was identified, including caffeic acid and ferulic acid. John and Shahidi [68] reported that the total soluble phenolic content of the date seeds ranged from 68.7 to 82.6 mg GAE/g, and several phenolic compounds were also identified in their date seed extracts, including proanthocyanidin dimers, catechin, epicatechin, and others. The extract of soluble phenolic from date seeds is effective in preventing DNA strand scission by 74.2% and can efficiently inhibit the mRNA level of COX-2 at concentrations as low as 5 µg/mL, which represents the potency of date seed samples in the inhibition of radical-induced DNA scission.

4. Valorization Approaches of Date Processing Waste

The valorization approaches of date processing waste are essential for several reasons. First and foremost, the disposal of date processing waste can have significant environmental impacts. The process of organic waste decomposition in landfills produces methane, a powerful greenhouse gas that contributes to climate change [71]. By utilizing valorization approaches for date processing waste, it will be possible to redirect waste away from landfills and decrease the emission of greenhouse gases. In addition to the environmental benefits, valorization approaches for date processing waste can also lead to economic opportunities. Furthermore, the extraction of high-value compounds from date processing waste can create new markets for the food, cosmetic, and pharmaceutical industries [72]. Moreover, valorization approaches for date processing waste can also become a source of renewable energy. The production of biofuels and organic waste can be subjected to anaerobic digestion to produce electricity and heat, which can be used to power homes, buildings, and industrial processes [73]. Another reason to utilize date processing waste is to improve the sustainability of the date industry and reduce costs. Disposing of date processing waste can be expensive, so finding ways to convert it into valuable products may reduce costs and make the industry more sustainable [17]. The valorization of date processing waste, by transforming it into value-added products, represents an innovative solution that addresses both waste reduction and the creation of new economic opportunities (Figure 4).

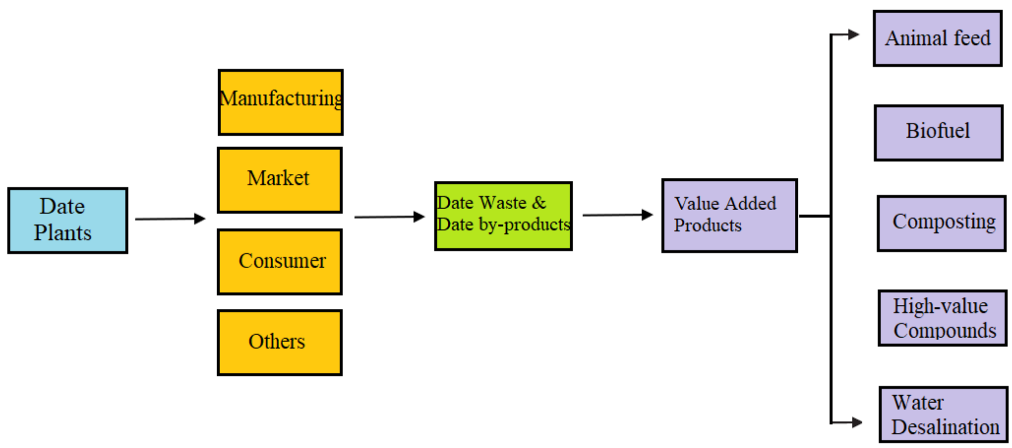


Figure 4. Opportunities of date waste valorization.

Overall, the valorization approaches of date processing waste are crucial for sustainable development. These approaches may create a source of renewable energy, animal feed, and materials and help to reduce the environmental impact of waste disposal and create economic opportunities. The possible valorization methods of date by-products are listed in Table 4.

Table 4. Possible applications of date by-products for their valorization.

By-Products	Possible Use	Product	References
Low-grade dates	Juice and following product production	Date juice; concentration: date spread, syrup and liquid sugar; fermentation: wine, alcohol, and vinegar	[5,13]
	Composting	Nutrient-rich fertilizer	[74]
	Biofuel production	Ethanol	[75]
Date processing wastes	Phenolic compound extraction	Used as raw materials or additives in food, health supplement, pharmaceutical, and cosmetic areas	[76]
	Animal feed	Ostrich chick feed additive	[77]
	Fiber extraction	Functional fiber ingredients in food industry	[78]
	Soap production	Soap formula additives	[79]
Date pits	Food packaging	Improved film	[80,81]
	Oil production	Date pit oil	[10,19]
	Phenolic compound extraction	Used as raw materials or additives in food, health supplement, pharmaceutical, and cosmetic areas	[10,76]
	Water desalination	Coagulant and flocculant	[82]
Date leaves	Water desalination	Adsorbent	[83]
Date seed oil	Palm olein alternative	Cooking oil	[20]
	Biofuel production	Bio-jet fuel; green diesel	[22]
	Margarine production	Crucial ingredient	[19]
	Participate in cosmetic formulations	Body creams, shaving soap, and shampoo	[21]

4.1. Conversion of Date Processing Waste to Animal Feed

The conversion of date processing waste into animal feed is an important valorization approach due to its nutritional benefits, abundance, and availability. Animal feed produced from date processing waste is high in fiber and carbohydrates, which are essential nutrients for livestock and poultry [16]. Boufennara et al. [84] found that date processing waste is particularly useful for animal feed production, as it is readily available in regions where the date industry is prevalent.

Various methods can convert date processing waste into animal feed, including ensiling, drying, and pelletization. Ensiling is a useful method for the safe and long-term preservation of moist biomass, while minimally impacting the nutritional quality of the biomass [85]. Drying is a practical technique that reduces the moisture content of a product, resulting in increased stability and facilitating its transportation. Pelletization can improve the handling and storage properties of the feed [86,87]. The use of date processing waste as animal feed has several advantages. Najafi et al. [77] observed that incorporating up to 30% whole date waste into the diets of ostrich chicks not only ensures uncompromised growth performance but also holds the potential to improve stress-related variables and antioxidant status in growing ostriches.

However, using date palm waste as a source of animal feed is also challenging. For example, economically, it raises questions about the cost-effectiveness of transforming waste into feed, as well as issues related to transportation. Nutritionally, questions arise about whether animal feed derived from date palm can meet the animals' dietary requirements and the need for potential formulation improvements. Furthermore, safety considerations encompass compliance with food laws and potential risks such as fungal and viral infections during the processing stages [88].

4.2. Production of Biofuels

Date processing waste can be converted into biofuels through various methods such as anaerobic digestion, fermentation, and pyrolysis [89]. The process of anaerobic digestion is characterized by the decomposition of organic matter in the absence of oxygen through the action of microorganisms, resulting in the production of biogas as a by-product [22]. Fermentation involves the conversion of sugars and carbohydrates into biofuels, such as ethanol and butanol [90]. Pyrolysis is a thermal decomposition process that converts organic matter into bio-oil, biochar, and syngas [91]. Biofuels produced from date processing waste have several advantages over conventional fossil fuels. For example, they are renewable, biodegradable, and emit fewer greenhouse gases [92]. Biofuels can also provide economic opportunities for farmers and feed producers by creating a new market for date processing waste [93].

Research has shown that date processing waste can be a valuable biofuel feedstock. The substantial lignocellulosic composition and fatty acid characteristics found in date palm seeds offer a compelling opportunity for cost-effective and sustainable biofuel production as a readily available secondary biomass resource [94]. The obtained date-seed-derived pyrolysis oil used as a potential feedstock for producing alternative fuels is chemically and thermally stable and contains some value-added chemicals [95]. Rambabu et al. [22] investigated the use of tantalum phosphate (TaPa) as a hydroprocessing catalyst for the drop-in biofuel production from date palm seed oil under mild experimental conditions. The optimized one-step reaction yielded high quantities of deoxygenated hydrocarbons, including 53.6% bio-jet fuel (C_9–C_{15}) and 35.9% green diesel (C_{14}–C_{20}). For instance, a study conducted by Taghizadeh-Alisaraei et al. [75] investigated the potential of date processing waste as a feedstock for biogas production through direct sugar fermentation, direct gasification, pretreatment hydrolysis fermentation, and pretreatment saccharification/co-fermentation or fermentation. According to their results, the date processing waste had a high bioethanol yield, making it a suitable feedstock for biogas production. Similarly, a study by Ahmad et al. [96] investigated the possible application of date processing waste for producing ethanol through fermentation. According to the study, the high concentration of fermentable sugars in date processing waste indicates that it could serve as a valuable raw material in bioethanol production.

Despite the potential of date processing waste for biofuel production, some challenges must be addressed. For example, the high lignocellulosic content of date processing waste can make it difficult to convert it into biofuels using certain methods, such as fermentation [97]. In addition, the variability of date processing waste composition can also affect the quality and quantity of the biofuels produced [75]. So, producing biofuels using date processing waste is a promising valorization approach that can provide a renewable and sustainable alternative to fossil fuels. However, there are still challenges to be overcome for an efficient conversion of this waste into fuel.

4.3. Composting

The decline in soil fertility causes a serious environmental challenge, leading to various harmful consequences [98]. Firstly, it reduces crop yields and quality, impacting the sustainability of agricultural production. Secondly, declining soil fertility can trigger soil erosion, leading to land infertility and disrupting the ecological balance. Additionally, fertility decline may result in soil acidification, alkalization, or salinization, threatening plant growth. Most importantly, reduced fertility puts additional pressure on agriculture, prompting farmers to use excessive chemical fertilizers and pesticides, causing soil and water pollution [99].

Therefore, composting as an effective soil improvement method was introduced to solve this problem. Composting transforms organic waste into organic fertilizers, enhancing soil organic matter content, which also improves soil structure, enhances soil aeration, water retention, and provides essential nutrients for plant growth. Moreover, the organic matter generated during composting enhances soil resilience, reducing reliance on chemical fertilizers and promoting soil fertility restoration, thus increasing crop yields [100]. And date processing waste is an excellent source of organic matter, as it is rich in carbohydrates, fiber, and other nutrients, being a suitable candidate to be composed. The composting of date processing waste can be achieved through various methods, such as windrow composting, vermicomposting, and in-vessel composting. Windrow composting involves piling the date processing waste into long rows and periodically turning it to promote aeration and decomposition [101]. Vermicomposting involves using earthworms to break down waste, producing a high-quality compost rich in beneficial microorganisms and nutrients [102]. In-vessel composting involves using enclosed containers to control the temperature, moisture, and aeration of the composting process, producing faster and more efficient decomposition of the waste [103].

The compost produced from date processing waste can be used as a soil amendment or fertilizer, providing numerous benefits for plant growth and soil health. For example, a study by Abid et al. [104] showed that the application of date processing waste compost significantly increased the growth of tomato plants and improved the soil structure and fertility. Similarly, Benabderrahim et al. [74] found that the application of date processing waste compost improved the growth and yield of forage alfalfa and increased the soil's nutrient content.

Overall, composting is a valuable valorization approach for date processing waste, providing a sustainable and nutrient-rich organic fertilizer for plant growth and soil health. With further research and development, this approach could become a cost-effective and environmentally friendly solution for the date industry.

4.4. Extraction of High-Value Compounds

Date processing waste is a significant source of high-value compounds such as antioxidants, flavonoids, phenolic acids, and dietary fibers [17]. Different methods can be used to extract high-value compounds, especially phenolic compounds, from date processing waste, including solvent extraction, supercritical fluid extraction, and microwave-assisted extraction. Solvent extraction is one of the most commonly used methods, which involves the use of solvents such as methanol, ethanol, and acetone to extract target compounds from the waste [105]. For instance, Habchi et al. [76] conducted a study investigating the extraction of phenolic compounds from date pits using reflux solvent extraction. In their results, the extraction process was efficient, and the phenolic extracts had high antioxidant activity. Similarly, a study by Ghafoor et al. [10] explored the use of supercritical fluid extraction to extract phenolic compounds such as phenolic acids and flavonoids from date palm pits. This method utilizes supercritical carbon dioxide to extract the compounds. The study found that the extraction process had higher efficiency than conventional extraction and Soxhlet extraction, and the extracts had potential applications in the food and pharmaceutical industries. This method has the advantage of being environmentally friendly and producing high-quality extracts [10]. Extraction with microwave assistance is a relatively newer method that involves using microwave radiation to extract the compounds from the waste. This method is known to be efficient, fast, and environmentally friendly and was previously applied by Pourshoaib et al. [106] to recover phenolic compounds from date palm seeds, and the extracts were obtained within 5 min as a fast extraction.

4.4.1. Antibacterial Compound and Antioxidant Compound

The extracted high-value compounds from date processing waste can be applied in the food, pharmaceutical, and cosmetic industries. For instance, natural preservatives derived from high-value compounds extracted from date processing waste can be used to increase the shelf life of food products without relying on synthetic preservatives and the same for use as colorants [107,108]. Additionally, these compounds have potential health benefits, such as reducing the risk of chronic diseases and improving gut health [26]. Furthermore, phenolic compounds extracted from date processing waste have potential as natural remedies for various skin conditions such as acne and wrinkles [21]. High antioxidant phenolic extract from date fruit syrup waste is an effective additive in soap formulations. Rambabu et al. [79] investigated a more environmentally friendly approach to soap manufacturing by utilizing natural ingredients as a potential substitute for synthetic chemicals commonly employed in soap production. As a result, the soaps produced from the waste extract of date fruit syrup exhibited physicochemical properties that were similar to those of commercially available turmeric soap. Furthermore, antibacterial assays demonstrated the enhanced bactericidal properties of date fruit syrup waste extract soaps against Gram-positive *Streptococcus pyogenes* and Gram-negative *Pseudomonas aeruginosa* bacteria.

A series of gelatin blend films with date fruit waste extract were developed by Rangaraj et al. [80]. The hydrophilic properties of the extract improved water solubility but reduced tensile strength and increased flexibility in the films. Films with 25% extract had higher water vapor permeability due to plasticizing effects. These films released active phenolic compounds and had better antioxidant capacity than fatty food simulants in aqueous food. In canola oil storage tests, films with extract showed lower peroxide and Totox values than pure gelatin films. Date fruit waste extract is a promising natural antioxidant for enhancing food packaging film functionality and performance. Farousha et al. [81] also developed date-seed-extract-encapsulated mesoporous MCM-41 material, to extend the shelf life of food in food packaging applications, and the in vitro release performance and antioxidant and antimicrobial activities were investigated. As a result, date seed extract was successfully encapsulated into MCM-41 with a 1:1 weight ratio using vacuum adsorption, achieving a high encapsulation efficiency of 91%. DSE@MCM-41 exhibited sustained release in both acidic (pH 5.2) and alkaline (pH 7.4) environments without a burst effect, following a first-order release model regulated by the carrier structure. It showed a more sustained release of bioactive compounds and antioxidants than free date seed extract when stored at 4 °C for 90 days. Additionally, DSE@MCM-41 demonstrated stable antibacterial activity even after 72 h against *E. coli* and *S. aureus*, attributed to sustained DSE release from the encapsulated MCM-41 matrix. These findings suggest the potential of DSE-encapsulated MCM-41 as a nanocarrier for sustained-release food packaging systems to extend food shelf life.

4.4.2. Dietary Fiber

Date processing waste has high dietary fiber content, including cellulose, hemicellulose, and lignin. Studies have indicated that these types of fibers found in diets offer several health advantages, such as enhancing the digestive system and minimizing the probability of developing long-term illnesses [109,110]. Several studies have investigated the extraction of dietary fibers from date processing waste using different methods, including enzymatic hydrolysis, acid and alkali treatments, and microwave-assisted extraction [78,111]. The extracted dietary fibers can be used as functional ingredients in the food industry, such as in the production of high-fiber bread, pasta, and snacks, as well as in the development of dietary supplements [112].

4.4.3. Minerals

Similarly, the date processing waste is a rich source of essential minerals such as K, Mg, Ca, and Fe, and the recovery of these minerals from date processing waste can offer a sustainable and cost-effective solution for the food and supplement industry. The extraction of minerals from date processing waste can be achieved through different methods, such as acid extraction, enzymatic hydrolysis, and microwave-assisted extraction [27]. The extracted minerals can be used in various applications, such as in the production of dietary supplements or as food fortifiers to increase the nutritional value of processed foods.

Extracting valuable compounds from date processing waste is a promising method to produce value-added products using this abundant waste stream. Using green extraction methods and identifying novel bioactive compounds offer opportunities for economic and environmental sustainability in the date industry. Further research and development in this field are needed to optimize the extraction processes and to identify new applications for the extracted compounds.

4.5. Water Desalination and Purification

Water scarcity is a growing concern worldwide, and many regions are turning to desalination as a means of addressing the issue. Desalination refers to the technique of separating salts and other minerals from seawater or brackish water to make it potable and suitable for consumption and irrigation purposes [113]. However, desalination is an energy-intensive process and can have environmental impacts, such as the discharge of brine into the ocean [113]. One potential solution to these challenges is the use of date processing waste in desalination processes.

Date processing waste, such as date pits and leaves, contain high amounts of tannins and other organic compounds that can be used in the desalination process. The potential uses of date processing waste include its application in seawater pretreatment as a preliminary step before desalination [114]. Pretreatment is a critical step in desalination that involves removing suspended solids, colloids, and other impurities from the feed water [114]. Date processing waste can be used as a natural coagulant and flocculant to enhance the removal of impurities during pretreatment [114].

Rambabu et al. [115] investigated the utilization of date palm empty fruit bunches (DPEFBs) as a sustainable biosorbent for hexavalent chromium (Cr^{6+}) removal from synthetic wastewater. The pretreated DPEFB was analyzed for its morphology and surface chemistry using scanning electron microscopy, energy dispersive elemental analysis, and Fourier-transform infrared spectroscopy. Various biosorption parameters, including pH, biosorbent dosage, contact time, temperature, initial feed concentration, and agitation speed, were examined for their impact on Cr^{6+} removal by DPEFB, and they found that the DPEFB sorbent exhibited an isoelectric point at pH 2, becoming dehydronated above this value to capture positively charged Cr^{6+} ions. Optimal conditions for chromium removal were identified as pH 2, 0.3 g dosage, 100 rpm agitation speed, 120 min contact time, 50 mg/L initial feed concentration, and 30 °C operational temperature. Furthermore, DPEFB demonstrated reusability with $NaNO_3$ as an effective regenerant, allowing for up to three successive biosorption–desorption cycles without significant loss in efficiency. This study establishes DPEFB as an efficient, cost-effective, and eco-friendly biosorbent for removing toxic Cr^{6+} ions from wastewater, offering a sustainable approach to address this environmental concern. Date-palm-coir-waste-derived nano-activated carbon (DPC-AC) as a cost-effective solution for removing 2,4-DPA herbicide from the water was also investigated by Rambabu et al. [116]. DPC-AC, created through a one-step process, exhibited strong adsorption properties with a 98.6% removal rate under optimal conditions. It followed Langmuir isotherm and pseudo-second-order kinetics, and thermodynamic analysis confirmed its efficiency. The study also highlighted the nanosorbent's electrostatic and chemical interactions with 2,4-DPA, showcasing its potential for water treatment. Additionally, cost analysis and regeneration tests emphasized its economic feasibility and reusability, turning date palm coir waste into a valuable resource for pollution control.

In a recent study conducted by Rambabu et al. [83], they successfully demonstrated the effective treatment of aqueous effluents containing the 2,4-DPA herbicide using modified date palm leaf waste with sulfuric acid. The resulting product exhibited an amorphous structure characterized by numerous cavities, pore connectivity, and oxygen-bearing functionalities, facilitating the efficient removal of 2,4-DPA from water sources. The adsorption process was favorable, spontaneous, and exothermic from a thermodynamic standpoint. Additionally, reusability tests confirmed that the product could be regenerated using a NaOH regenerant and employed for up to five cycles to remediate 2,4-DPA-contaminated wastewater. Crucially, the adsorbent product demonstrated a remarkable remediation efficiency of 69.4% when applied to the treatment of actual agricultural runoff contaminated with 2,4-DPA herbicide, underscoring its readiness and potential for real-world applications. This study effectively valorized date palm leaf waste as a valuable adsorbent through a simple and cost-effective method for addressing the issue of agricultural wastewater pollution caused by harmful herbicides.

The process of pyrolysis was employed to create biochar from date seed biomass, and the current study reveals that the porous activated carbon known as DSAC-1:1.5 is a practical and high-performing electrode material suitable for capacitive deionization in desalination applications [82]. According to the study by Hai et al. [82], an optimal weight ratio of 1:1.5 (biochar: KOH) resulted in mesoporous date seed biochar-activated carbon with a uniform structure. It displayed amorphous and graphitic carbon formation due to KOH activation, offering a mixed micro- and mesoporous nature. Electrochemical tests revealed a specific capacitance of 400 F g^{-1} for DSAC-1:1.5, making it suitable for NaCl desalination, achieving 22.2 mg gm^{-1} electrosorption capacity and 86.4% charge efficiency. The electrode proved reusable for six cycles without performance decline. This low-cost date seed biochar-activated carbon outperforms existing carbon-based electrodes in desalination applications.

While the use of date processing waste in water desalination shows promise, several challenges must be addressed. One such challenge is the variability of the chemical composition of date processing waste, which can affect the effectiveness of the pretreatment and the performance of the desalination membranes [117]. This challenge can be overcome through proper selection and processing of the raw materials to ensure consistency in the quality of the bioactive compounds [117]. However, most current research in this area has only been conducted on a laboratory scale, and more research is required to determine the feasibility of large-scale production and commercialization of these products [118,119]. Finally, the regulatory and environmental impacts of using date processing waste in desalination processes need to be further studied to ensure no unintended negative consequences.

5. Challenges and Future Perspectives

Date palm waste valorization presents opportunities and challenges critical to address for sustainable and environmentally friendly resource management. These waste materials can be transformed into valuable products through the above valorization processes. However, unlocking the full potential of date palm waste valorization requires overcoming several key challenges while considering future perspectives for sustainable practices.

One of the challenges in date palm waste valorization is the efficient collection and transportation of waste materials from date palm farms to processing facilities. Given the often remote and dispersed locations of date palm plantations, logistics and infrastructure for waste collection can be costly and complicated. Innovations in collection and transportation methods, such as mobile chipping and shredding units, can help mitigate this challenge by reducing transportation costs and increasing the feasibility of waste utilization.

The variability in the composition and quality of date palm waste is another significant obstacle. Date palm waste consists of various components, including fronds, pits, coir, and leaves, each with different properties and potential applications. This heterogeneity demands tailored valorization approaches for different waste components. Developing efficient separation and sorting techniques to segregate these components and optimize their utilization is essential for maximizing the value of date palm waste.

Future perspectives for date palm waste valorization involve exploring advanced technologies and innovations to enhance its efficiency and sustainability. One such innovation is the integration of biorefinery concepts, where multiple products and value streams are extracted from date palm waste. This approach can involve the simultaneous production of bioenergy, biofuels, bioplastics, and bioactive compounds from different waste components, leading to a more comprehensive and profitable resource utilization.

Biotechnological advancements, including the development of genetically modified date palm varieties with enhanced biomass properties or improved bioactive compound content, hold the potential for optimizing date palm waste valorization. Genetic engineering can increase yields and improve properties, making date palm waste a more attractive feedstock for various applications.

Furthermore, research into the utilization of date palm waste for producing bioenergy and biofuels, such as biogas, bioethanol, and biodiesel, is a popular and promising recent avenue. Advanced conversion technologies, such as anaerobic digestion, pyrolysis, and gasification, can efficiently convert date palm waste into renewable energy sources, reducing dependence on fossil fuels and mitigating greenhouse gas emissions.

6. Conclusions

Date palm fruit, known for its nutritional richness, holds great promise for producing value-added products in the food and nutraceutical industries through bioprocessing technologies. The substantial quantities of date seeds and discarded fruits offer untapped potential for bioprocessing, opening doors to new product possibilities. Additionally, the efficient utilization of date palm fruit, which is rich in carbohydrates, dietary fiber, and bioactive compounds like phenolic compounds, can be achieved through various extraction methods applied to date processing wastes, serving as essential ingredients for diverse value-added products across various industries. As stated in this review, date palm waste materials have versatile applications beyond traditional use, such as animal feed. Recent research has also shown that they can be utilized for biofuel production, composting, antimicrobial and antioxidant additives, and water desalination and purification. The abundance of date fruit by-products and waste, particularly the vast reserves of unused date seeds, holds immense potential for novel product development. Date-palm-growing countries can leverage this opportunity to fully exploit the date palm's potential, manage waste effectively, and create opportunities for rural and socioeconomic advancement.

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