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Comparative evaluation of ultrasound-assisted extraction with other green extraction methods for sustainable recycling and processing of date palm bioresources and by-products: A review of recent research

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ABSTRACT

The global food waste crisis has significantly contributed to climate change, water pollution, and land degradation. Date palm waste, including seeds, fronds, and fruit pulp residues, represents a valuable source of bioactive compounds with potential applications in food, pharmaceutical, and cosmetic industries. This study presents a comparative evaluation of ultrasound-assisted extraction and other novel extraction techniques, such as pressure-based extraction, pulsed electric fields, microwaves, and natural deep eutectic solvents, for recovering bioactive compounds from date palm waste. These methods were assessed for their efficiency and sustainability in extracting antioxidants and phenolic compounds, and other bioactives while minimizing the use of harmful solvents and high temperatures. Critical factors, such as extraction time, solvent type, temperature, and pressure were crucial indicators to achieve higher extraction efficiencies with lower environmental impacts compared to traditional methods. Additionally, combining these techniques may further optimize the extraction process. This study contributes to the development of sustainable strategies for valorizing date palm byproducts and promoting a circular economy in the food industry. By developing sustainable extraction methods that minimize environmental impacts, this research directly supports the United Nations' Sustainable Development Goals, particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

1. Introduction

Date palm (*Phoenix dactylifera* L.) is a resilient crop with profound significance in Islamic culture and is a rich source of medicinal and commercial benefits [1]. Thriving in arid environments, it is predominantly cultivated in North Africa, the Middle East, and select regions of the Americas, contributing approximately 75 % of global date fruit production [2]. In 2021, the leading producers included Egypt (1.7 million metric tons), Saudi Arabia (1.5 million metric tons), and Iran (1.3 million metric tons) (Fig. 1) [3]. However, the expansion of date production has resulted in substantial waste generation, comprising leaves, pits, and spikelets, which can be repurposed as valuable sources of bioactive compounds for various food applications [4].

Despite its potential benefits, the date-processing industry encounters significant postharvest challenges. Approximately 20 % of the annual date production is lost due to over-ripening, improper handling and storage conditions, cross-contamination, and inadequate packaging strategies [5]. This waste not only represents a loss of resources but also contributes to environmental degradation, with the FAO estimating that global date palm waste and byproducts amount to approximately 8–12 million tons annually [2]. The abundance of date palm byproducts presents an untapped resource for sustainable extraction of bioactive compounds, addressing both food waste and the demand for natural antioxidants. Utilizing date byproducts as an alternative source of antioxidants instead of synthetic options not only conserves resources but also reduces the carbon footprint associated with the extraction processes [6]. Traditional methods, including maceration, Soxhlet extraction, and solvent-based techniques, have been widely utilized for recovering bioactive compounds from date palm and its byproducts. For example, maceration with water and organic solvents has been

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employed to extract polyphenols and flavonoids from date fruit or byproducts, yielding antioxidant-rich extracts [7,8]. Similarly, Soxhlet extraction has been applied to date seeds to recover oil and phenolic compounds, though the prolonged exposure to high temperatures during the process risks degrading thermolabile compounds [9,10]. These traditional techniques, while effective in many cases, are associated with several limitations, including lengthy extraction times, high solvent consumption, and significant environmental burden. Solvent-based extraction using methanol and acetone has been extensively explored for isolating phenolics, flavonoids, and antioxidants from dates, showing promising yields but raising concerns about solvent toxicity and environmental impact [11]. These methods often rely on organic solvents, such as methanol, which has been shown to be more effective than ethanol or water for extracting polyphenols; however, these methods are costly and environmentally harmful [12–14]. Other conventional techniques, such as immersion and thermal extraction, not only require expensive solvents but also pose safety hazards and contribute to greenhouse gas emissions due to high energy demands [4,15]. These drawbacks highlight the need for greener and more efficient alternatives for valorizing date palm byproducts sustainably.

Recent trends have highlighted the emergence of non-thermal green extraction methods that enhance sustainability in recovering bioactive components from agro-waste [16,17]. Among these methods, ultrasound-assisted extraction (UAE) and pressure-based extraction (PBE), including supercritical fluid extraction (SFE) and pressurized liquid extraction (PLE), have shown promise for recovering phenolic compounds from date palm byproducts [6,18]. Furthermore, integrating UAE and PBE with advanced technologies, such as pulsed electric fields (PEF) and microwave techniques, and green solvents, such as natural deep eutectic solvents (NADES), can significantly improve the bio accessibility of functional ingredients [19–21].

Despite these advancements in extraction methodologies, a notable gap remains in comparative studies that directly juxtapose UAE and PBE, specifically for extracting bioactive compounds from date palm byproducts. Most of the existing literature focuses on either method independently, without providing a comprehensive comparison that can elucidate their relative efficiencies and sustainability profiles [22–24] This review aims to fill this gap by systematically assessing these innovative extraction methods, while emphasizing their potential to transform date palm byproducts into valuable resources for health applications. Addressing the valorization of date palm waste not only aligns with general sustainability practices, but also directly contributes to achieving the United Nations Sustainable Development Goal 12.3, aimed at reducing food waste.

2. Comparative evaluation of sustainable green extraction techniques for processing of date palm byproducts

2.1. Ultrasound-assisted extraction (UAE)

Compared with conventional food extraction methods, UAE offers multiple advantages, including enhanced safety and efficacy, making it a superior alternative for the food industry [25]. UAE employs high-frequency sound waves (20 kHz to 100 kHz) to induce cavitation, which is characterized by the formation and subsequent collapse of microbubbles within the solvent [26]. This process significantly enhances solvent penetration into cell matrices, thereby facilitating the efficient release of intracellular compounds. Low-frequency range (20–40 kHz) is more commonly used for applications like cavitation, as it generates intense mechanical effects suitable for breaking cell walls and enhancing extraction efficiency. Whereas high-frequency range (40–100 kHz) produces less intense cavitation but offers more controlled and efficient extraction for sensitive bioactive compounds. UAE is particularly effective for polyphenols, carotenoids, aromatic compounds, and polysaccharides [27]. The cost-effectiveness of the UAE, when compared to other non-thermal technologies such as PEF or high hydrostatic pressure, enhances its feasibility for widespread industrial adoption across various food sectors [25]. Given its secure, non-polluting, and environment-friendly characteristics, ultrasound technology aligns well with the principles of the circular food economy, promoting sustainable production methods [28].

As a distinguished nonthermal extraction technique, UAE harnesses high-frequency sound waves to efficiently liberate valuable compounds from plant materials, thereby offering an alternative to heat-based extraction methods [29]. UAE systems are predominantly categorized into two types: probe-type and bath-type, as shown in Fig. 2(a) and (b), each selected based on sample characteristics and experimental conditions. High-frequency vibrations have a mechanical effect on the sample,

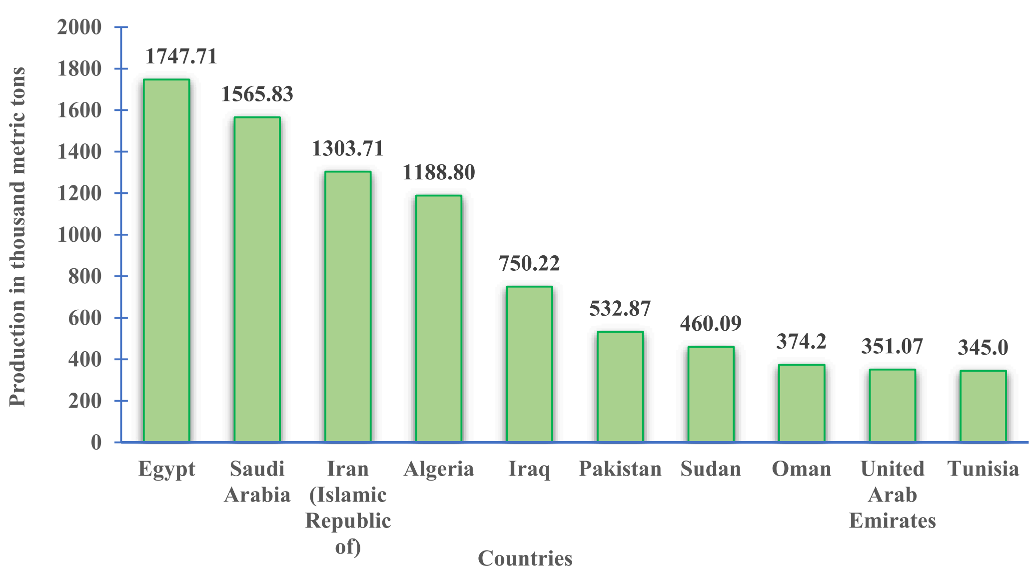

Fig. 1. Production of dates: Top ten producers in 2021 (. Source: FAO 2023)

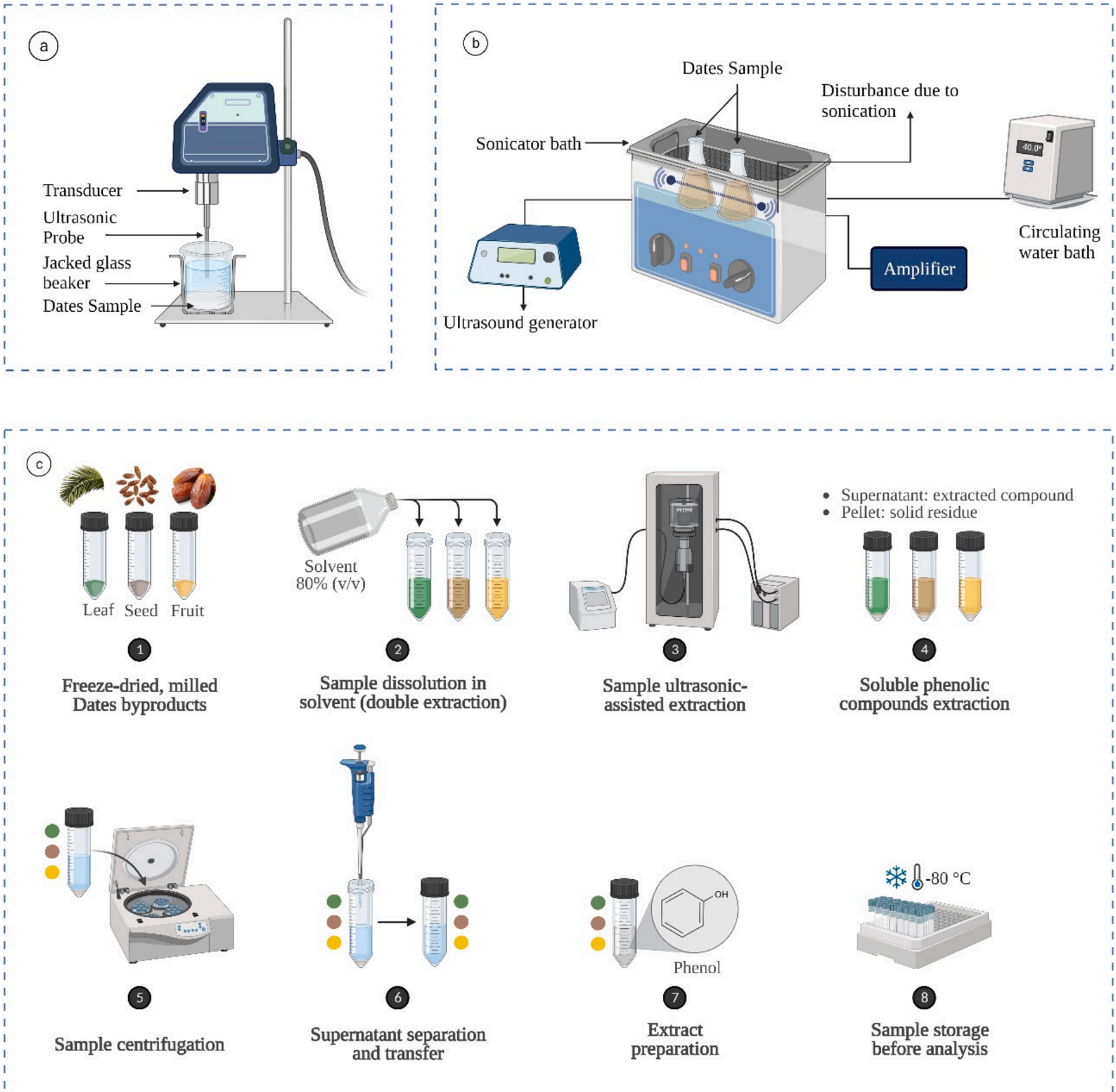

Fig. 2. (a) Ultrasound-assisted extraction (USAE) assembly with probe and (b) bath extraction; (c) schematic representation of bioactive compound extraction process using USAE.

causing the breakdown of the cellular structure and releasing selective content into the solvent [30], as demonstrated in Fig. 2(c). Compared to traditional extraction techniques, ultrasound can improve the extraction of polar and thermally labile compounds, increase the extraction efficiency and yield, and decrease the extraction time [31].

Given its numerous advantages, UAE has been extensively applied for the extraction of valuable compounds from date palm waste, demonstrating its potential for sustainable waste valorization. Several studies have shown that UAE is effective for extracting natural sugars and phenolic compounds [32–34] (Table 1). Recently, UAE has been used to retrieve various bioactive compounds from agro-food waste, including fruit seeds [35,36], peels [37], leaves [24], and vegetables [39]. In the context of date palm waste, traditional extraction methods often fail to efficiently recover bioactive compounds due to the tough fibrous nature of the waste, making UAE a superior alternative. UAE has been extensively studied for its efficacy in extracting bioactive and phenolic compounds from date byproducts including date seeds and spikelet [4]. For instance, date palm spikelet is rich in phytochemicals, such as rutin and (+)-catechin, which are known for their potent antioxidant properties. Typically discarded, these byproducts present significant environmental and economic challenges owing to disposal issues.

2.1.1. Recovery of bioactive compounds from different date palm products/by-products using UAE

The application of UAE has been shown to enhance the extraction

Fig. 3. Circular bioeconomy of date palm by-products in the food system.

yield of phenolic compounds, which are known for their antioxidant properties [40–42]. For instance, studies have demonstrated that UAE can outperform traditional extraction methods such as maceration and reflux extraction in terms of yield and extraction speed [43]. Specifically, the use of UAE has been linked to a reduction in solvent consumption and extraction time, making it a more eco-friendly option compared to conventional methods [44].

A critical aspect of UAE is its impact on the recovery efficiency of valuable bioactive compounds [45]. Reflecting on the discussed benefits of UAE, studies have shown that optimizing UAE parameters, such as solvent concentration and sonication time, can significantly enhance the yield of phenolic compounds from date palm spikelet. The optimization of the UAE process using the Box-Behnken design focused on critical factors such as processing temperature, duration, and ethanol concentration [4]. Under optimal conditions of 50 % ethanol concentration, 4 °C, and a duration of 22 min, the highest radical scavenging activity (87 % DPPH inhibition) and total phenolic content (TPC) recovery (124 mg GAE/g) were achieved. These findings indicate that both temperature and ethanol concentration are pivotal in determining the TPC and radical-scavenging activity. Higher temperatures facilitate the release of functional compounds from date palm seed extracts by disrupting cell wall membranes, thereby enhancing mass transfer and diffusion. Conversely, increased ethanol concentrations improved the solubility of phenolics, leading to extracts with enhanced antioxidant activity [46]. Notably, it was observed that either a high temperature with reduced ethanol concentration or a low temperature with high ethanol concentration can optimize TPC extraction, whereas a high ethanol concentration at low temperatures can enhance radical scavenging activity [4]. However, prolonged sonication can degrade sensitive phenolic compounds or introduce contaminants, potentially reducing the overall phenolic content [47].

A comparative analysis of different solvent systems and extraction techniques indicated that water and ethanolic solvents are more effective than acetonic solvents in enhancing the levels of phenolics, flavonoids, and condensed tannins in roasted date seeds [34]. Although maceration yielded the highest extraction rates, UAE and microwave-assisted extraction (MAE) provided comparable results in significantly shorter timeframes. The saturation level of the solvent also plays a crucial role in the extraction yield; unsaturated conditions favor higher yields owing to enhanced diffusion [48]. Among the methods tested, UAE achieved the highest TPC, whereas MAE yielded lower TPC but required less than five minutes for extraction [34]. Ultrasound energy enhances particle movement and extraction yield [49], whereas MAE increases the extraction efficiency by elevating the internal pressure and cell membrane permeability [50].

UAE has also proven effective in recovering phenolics and bioactive compounds from date leaves, which are rich in polyphenols and have significant potential to combat free radical toxicity. Various solvents such as ethanol, methanol, hexane, and chloroform, along with extended sonication times and elevated temperatures, improve the extraction efficiency of phytochemicals from date leaves [51]. Optimal extraction conditions involving 80 mL of ethanol for 20 min yielded the highest phenolic content (298.34 mg GAE/g dry weight), correlating with the peak antioxidant and anti-inflammatory activities. However, exceeding these parameters leads to a decline in antioxidant activity.

Date palm also contain seeds with high protein contents that have been evaluated as sources of antioxidant peptides. UAE technology has been shown to enhance extraction yields while reducing processing time for date seed protein concentrate (DSPC) [52]. Optimal UAE conditions for DSPC treatment—an amplitude of 80 % and a frequency of 20 kHz for 15 min —resulted in significant improvements in emulsion activity, foaming ability, and oil-absorbing capacity. This treatment increased DSPC solubility by 131 %, from 14.1 % to 32.56 %. Additionally, while the foaming capacity and stability improved, the water-binding ability decreased [52]. Similarly, the extraction of proteins from date palm pollen has been explored, revealing that sonication can improve the physicochemical and functional properties of the extracted proteins. Sonication pretreatment enhanced the extraction efficiency and modified the structural properties of fibro-proteins from male date palm flowers, suggesting that UAE can be effectively utilized to extract proteins with desirable functional characteristics [53].

A study presented a novel strategy to valorize date seed waste by synthesizing date seed nanoparticles (DSNPs) through acid hydrolysis, followed by UAE to enhance their phenolic content and antioxidant properties [54]. The optimized synthesis method produced DSNPs with particle sizes ranging from 50 to 150 nm, achieved using 38 % HCl for 4–5 days, revealing that parameter such as ultrasound amplitude (90 %), treatment time (6–9 min), and solvent concentration significantly influenced the extraction efficiency. The study documented a maximum phenolic content of 63.64 mg GAE/g and notable antioxidant activities,

Table 1
Recent studies on ultrasound-assisted processing of date byproducts and waste.

Dates	Extraction	Experimental condition	Highlights	Reference
Date palm spikelet (*Khalas*)	TPC and DPPH radical scavenging activity	Ethanol concentration (25 %, 37.5 %, and 50 %), 25°C, 42.5°C, and 60°C for 20, 30, and 40 min.	The best TPC and DPPH recovery was achieved using ultrasonic extraction with 50 % ethanol at 40.8 °C for 21.6 min. Rutin and (+)-catechin were the primary phenolic compounds found.	[4]
Date fruit (*Tamdjohart*)	TPC and antioxidant activity	Methanol concentration (40–80 %), sonication amplitude (50–100 %) for 10–30 min.	The optimal combination for antioxidant extraction was 65 % methanol, 84.50 % ultrasound amplitude, and 17.64 min extraction time. TPC and antioxidant activity were 246.46 mg EAG/100 g and 26.48 mg EAG/100 g, respectively.	[125]
Date fruits (*Litim*)	TPC and antioxidant activity	Acetone concentration (40–80 %), sonication amplitude (50–100 %), for 15–35 min.	Acetone extraction (66.71 % for 29.58 min, sonication amplitude 64.78 %) yielded the highest TPC and antioxidant activity, with values of 725.33 and 39.61 mg GAE/100 g DM.	[30]
Date fruit and seed (*Medjool*)	Bioactive components	Solvent: 70 % ethanol, 70 % methanol, and Milli-Q® water + 5 min US ice water bath at an amplitude of 40 %.	US extraction using ethanol yielded the highest TPC in date seeds (18.53 mg GAE/g), while conventional extraction ranged from 1.30 to 14.46 mg GAE/g. The TPC and antioxidant capacity of phenolic compounds from date flesh were lower than those from seeds, with the highest values found in US-assisted seed samples extracted with methanol. The extract contained epicatechin (36.12 μg/g), coumaric acid (27.05 μg/g), p-hydroxybenzoic acid (21.03 μg/g), syringic acid (19.85 μg/g), and epicatechin gallate (11.67 μg/g).	[126]
Date seeds and leaves	Soluble and insoluble-bound phenolic compounds	Solvent: methanol-acetone–water (7:7:6, v/v/v) + UAE: 20 min at 30 ℃.	TPC of date palm leaves was 106.96 mg gallic acid equivalents (GAE)/g, while date seeds ranged from 68.73 to 82.62 mg GAE/g. Various phenolic compounds, including proanthocyanidin dimers, catechin, epicatechin, 5-O-caffeoylshikimic acid isomers, ferulic acid, rutin, and isorhamnetin hexoside, were identified in date palm seeds and leaves.	[127]
Date seed powder (*Khalas, Fardh* and *Khenaizi*)	Bioactive components	UAE: solid to liquid (water) ratio was 1:25 (w/v) and < 125 μm particle size, 90 % amplitude for 8 min at 30 °C.	Maximum TPC and TFC were 17.44 mg GAE/g and 9.086 mg QE/g, respectively. Antioxidant activities measured were 40.17 mmol TE/g (FRAP), 74.22 mmol TE/g (DPPH), and 21.61 mmol TE/g (ABTS). Among Khalas, Fardh, and Khenaizi varieties, Fardh exhibited the highest TPC, TFC, and antioxidant activity. All three varieties contained benzoic acid, catechin, vanillin, and ferulic acid as major polyphenols.	[100]
Date seed powder (*Medjool*)	Antioxidant activity	UAE: Ethanol (50–80 %), time (30–90 min) and temperature (40–70 °C)	The optimum conditions for maximum antioxidant activity (ABTS; 60.93 %) were achieved at 80 % ethanol, 44 min and at 57 °C, where the effect of ethanol concentration were notably significant.	[128]
Date byproducts (*Kabkab, Mozafati*, and *Sayer*)	Antioxidant activity	UAE: 70 % ethanol for 30 min at 30, 50, and 70 °C	Ultrasound treatment increased the extraction of polyphenols and flavonoids in all date varieties. The contents of these compounds rose with the extraction temperature up to 50 °C, then declined. The highest levels were observed in the *Sayer* variety at 50 °C with US treatment, yielding 4.64 mg Gallic acid/g and 0.326 mg quercetin/g, respectively.	[129]
Date fruit (*Degla-Beida*)	Pectin	40–60 °C for 30–90 min, and pH (1.5–3.5).	Optimum conditions (60 °C, 90 min, pH 1.5) yielded 6.7 %. UAE pectin had higher galacturonic acid and lower neutral sugars.	[33]
Date fruit powder (*Sukkari*)	Sugar	60 °C for 30 min, and liquid-to-solid ratio of 7.6 mL/g.	Ultrasonic treatment of biomass improved mass transfer diffusion, raising total sugar content (812 mg glucose eq./g) and extraction yield (81.40 %) of date fruit powder.	[32]

(*continued on next page*)

Table 1 (*continued*)

Dates	Extraction	Experimental condition	Highlights	Reference
Date Seed (*Saidy*) protein concentrates	Protein concentrate	20 kHz, amplitude of 40, 60, and 80 %, for 5, 10, and 15 min.	Ultrasound improved solubility, emulsion/foaming stability, and oil-binding.	[52]
Male date palm flowers extracts	Proteins	US probe at 20 kHz and the amplitude of 60 % for 2 s, followed by a 1-s pulse-off delay with a total sonication time of 30 min.	The fibro-protein extraction yield has increased leading to the amelioration of the protein recovery. The sonication pretreatment contributes to improving the amino acid profile and the protein solubility.	[53]
Date seeds (*Deglet Nour, Allig* and *Belah*)	Oil	Solvents: n-hexane and 2-methyltetrahydrofuran + UAE: 20 kHz, 130 W, at 40 °C.	In addition, extraction of oils from date pits with ultrasound and micro-wave were better in terms of extraction time (30 min versus 8 h) comparing to soxhlet procedure and of extraction yield comparing to maceration (about 6 % versus 4 %).	[9]
Date seeds (*Khalas*)	Bioactive nano-particles	Solvents (water and methanol) + UAE: amplitudes (70 %, 80 %, and 90 %), for 3, 6, and 9 min at 37–40 °C.	The TPC, TFC, and antioxidant activities of water-based UAE-extracted samples were primarily influenced by solid/liquid ratio (40:1 mg/ml) and treatment time (9 min). In contrast, methanol-based US-sample was predominantly affected by US amplitude/power (90 %) and methanol concentration (80 %).	[54]

Abbreviations: UAE: Ultrasound-assisted extraction; TPC: Total phenolic content; DPPH, 1-diphenyl-2-picrylhydrazyl.

assessed using assays such as DPPH, FRAP, and ABTS [54]. Enhanced antioxidant properties were attributed to the reduced particle size and improved bioavailability of phenolic compounds. These findings demonstrate the dual benefits of waste valorization and functional ingredient production, highlighting DSNPs' potential for applications in the food and nutraceutical industries.

2.1.2. Extraction of sugars

Dates are known for their high concentration of natural sugars, making them a valuable source of sweeteners such as date syrup [55]. This syrup is used in a variety of products, including jams, honey, ice cream, and sweets. Traditional methods of extracting date syrup involve boiling dates with water (70 °C for hours), which can result in nutritional losses and undesirable color changes. Furthermore, these methods are inefficient, with sugar recoveries ranging from only 40–50 % [56–58]. To overcome these limitations, innovative approaches have been investigated, including the use of UAE to extract date syrup from date fruit powder [32]. Optimization of the extraction process was accomplished by employing response surface methodology with a Box-Behnken design to achieve better results. The optimal conditions (60 °C for 30 min and 7.6 mL/g liquid-to-solid ratio) resulted in a significant enhancement of both sugar content and extraction yield. UAE has been proven to improve mass transfer and increase sugar yield, particularly at higher liquid-to-solid ratios and longer extraction times. However, prolonged extraction times and high concentrations of the extraction medium may reduce sugar content and yield [59]. Additionally, the sugar content and yield were reduced when the temperature exceeded 45 °C, as thermolabile sugar constituents were degraded, and impurities, including Maillard reaction products, were formed [60].

Enzymatic treatments with pectinase/cellulase and sonication enhanced the yield and quality of the extracted syrup [56]. Specifically, a combination of 25 % sonication power and a 1:3 date-to-water ratio resulted in a higher recovery of soluble solids (74.30 %) than traditional methods (58.45 %) and enzymatic treatments (66.70 %). Moreover, the syrup produced through sonication demonstrated superior quality, suggesting that 25 % sonication power is the optimal condition for obtaining higher yields of soluble solids from date pulp [56].

Pectin—a polysaccharide with diverse industrial applications—has traditionally been extracted using mineral acids at low pH levels (1.5–3.0) and high temperatures (60–100 °C for 0.5–6 h), often resulting in low yields and environmental concerns. In contrast, UAE conducted at 60 °C for 90 min at pH 1.5. successfully extracted pectin from an Algerian date variety, yielding a product with superior antioxidant and antidiabetic properties compared to acid-extracted pectin [33]. This includes higher galacturonic acid content, reduced neutral sugar content, and enhanced glucose adsorption capacity [61]. UAE also improved pectin purity by lowering glucose levels; samples exhibited a glucose content of 13.3 % compared to 20.2 % obtained through conventional methods. Furthermore, the glucose adsorption capacity of UAE-extracted pectin was higher (4 mmol/g) than that of its acid-extracted counterpart (2.6 mmol/g), attributed to its greater molecular weight (800 kDa) and viscosity characteristics [33]. Notably, treatment with nitric acid reduced the molecular weight of extracted pectin more significantly than UAE treatment alone, suggesting that UAE-derived pectin may offer additional health benefits [33]. Thus, UAE not only supports the efficient extraction of antioxidants and phenolic compounds, but also holds promise for the recovery of sugars and pectin, underscoring its versatility and potential in valorizing date palm waste.

2.2. Supercritical fluid and pressurized liquid-based extraction technology

Extraction techniques that rely on pressure are a sophisticated set of methods that utilize the principles of high pressure to facilitate the release of bioactive compounds from the plant matrices. Supercritical fluid extraction (SFE) and pressurized liquid extraction (PLE) have been successfully applied to date byproducts [62]. Subcritical water extraction (SWE) is an innovative method that has been extensively studied for its ability to effectively extract bioactive components [63]. For instance, SWE provided the highest yield of polyphenols and antioxidant activity compared to UAE, ultrasound-assisted subcritical water, and hot water extraction [64].

Subcritical carbon dioxide (SC-CO_2) is another extraction method uses the exceptional attributes of CO_2 in its subcritical state, which is an intermediate state in which it exhibits both liquid- and gas-like characteristics to penetrate solid matrices and selectively dissolve the target compounds [6]. This method is particularly beneficial because of its high selectivity, minimal solvent usage, and operation at relatively low temperatures, which are critical for maintaining the stability of heat sensitive substances. SC-CO_2 serves as a solvent for dissolving the desired compounds, which are subsequently collected in a separation vessel upon depressurization, leaving CO_2 to evaporate or be recycled [65]. This technique requires a sophisticated device, including an extraction vessel, high-pressure pumps for fluid transport, a co-solvent pump to enhance the extraction of polar molecules, a chiller, a back-pressure regulator, a separator, and a gas flow meter, as depicted in Fig. 4. The operational mechanism involves pressurizing and heating CO_2 above its critical point, which is subsequently introduced into an extraction vessel containing a date byproduct matrix [18].

Compared to other extraction techniques such as UAE and MAE, SC-CO_2 is particularly effective for extracting specific classes of bioactive compounds, including lipophilic compounds, phenolics, and certain vitamins [66]. These compounds are highly soluble in SC-CO_2 and can be

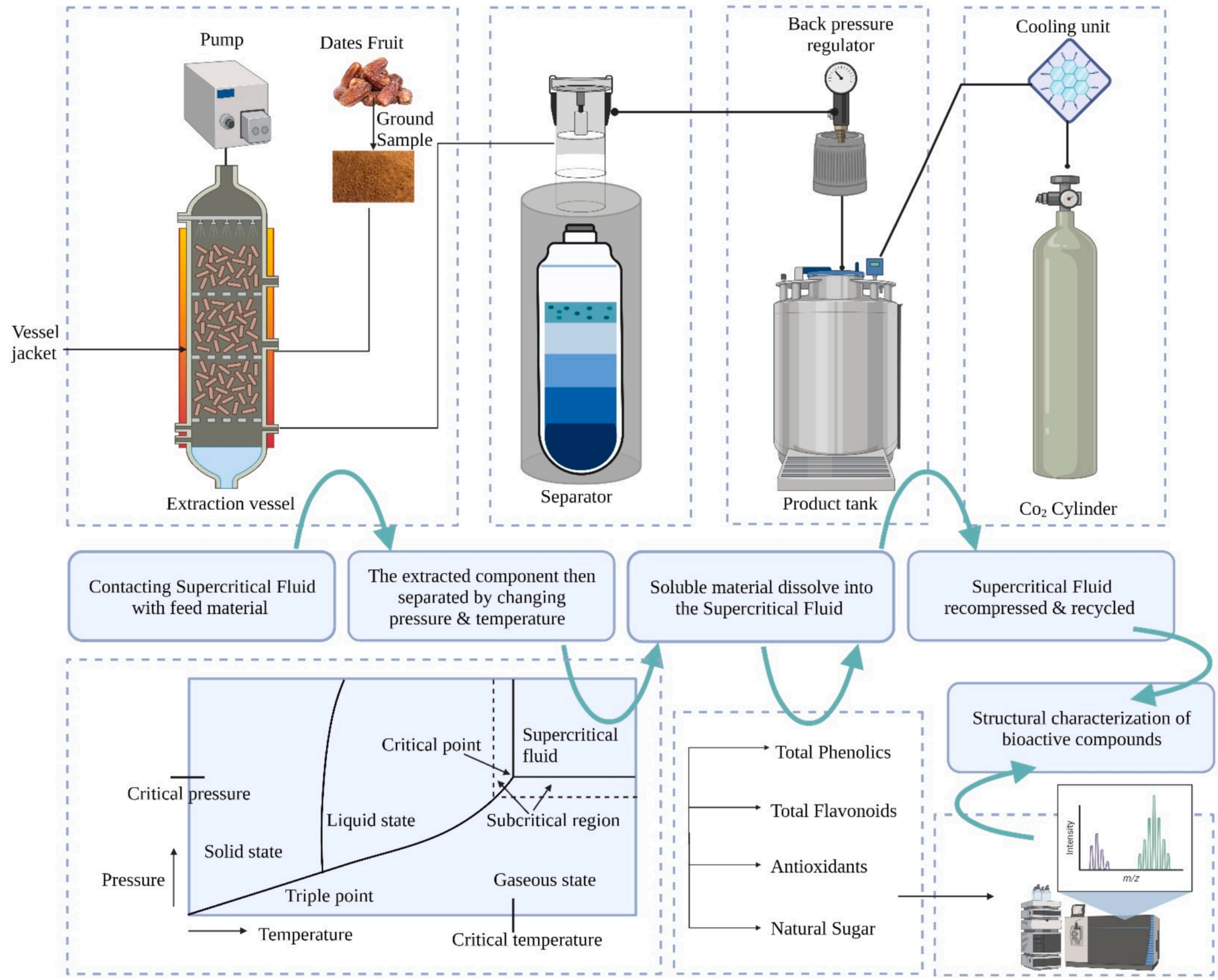

Fig. 4. Graphical description of the experimental setup for supercritical carbon dioxide extraction that schematically represents the pressure–temperature phase.

extracted at relatively low pressures (75–100 bar) [67]. One of the key advantages of SC-CO_2 is its ability to selectively extract non-polar and slightly polar compounds. For instance, SC-CO_2 has been shown to effectively extract vitamin E from *Spirulina*, highlighting its capability to concentrate specific bioactive compounds under optimized pressure and temperature conditions [68]. This selectivity is attributed to the tunable properties of CO_2, which can be adjusted by altering pressure and temperature to enhance the extraction of desired compounds [69]. Additionally, it may require the addition of co-solvents (e.g., ethanol, methanol, or water) to extract larger molecules and polar compounds effectively. The efficacy of this method has been substantiated through extensive reviews and empirical investigations that have elucidated the parameters influencing the extraction process, including pressure, temperature, and co-solvent [70].

The benefits of SC-CO_2 extraction go beyond its nontoxic and nonflammable properties, showcasing its advantages. This approach provides a sustainable and energy-efficient alternative to traditional methods that minimize the degradation of heat-sensitive compounds [71]. Unlike other methods, SC-CO_2 extraction does not produce harmful solvent residues, aligning with the increasing consumer demand for environmentally friendly natural products [70]. Although pressure-based extraction techniques show promise for sustainably recovering valuable compounds, they also present certain challenges that must be addressed.

The significant barriers to the widespread adoption of this equipment include its capital-intensive nature and the technical expertise required for operation. Additionally, the method may struggle with extracting highly polar compounds, which are often better suited for extraction via UAE or MAE [72]. Despite these challenges, the shift towards more sustainable and environmentally responsible production practices is expected to drive further advancements in the field. Ongoing research is expected to develop more cost-effective and efficient systems that can reduce entry barriers and facilitate broader applications, particularly in transforming food waste into valuable products [62]. However, these techniques are aligned with global trends toward sustainability and minimization of environmental impact, heralding a new era of green extraction technologies.

2.2.1. *Recovery of bioactive components*

Pressure extraction techniques, notably ultra-high-pressure extraction (UPE) and SC-CO_2 extraction have demonstrated efficacy in isolating a spectrum of bioactive substances from date waste (Table 2). UPE, particularly when applied at a pressure of 600 MPa and 65 °C with a 60.54 % ethanol concentration, was optimized using a Box-Behnken design to maximize the extraction of phenolics from date palms [73]. TPC peaked at 47.80 % ethanol concentration, while the total

Table 2
Sustainable green extraction methods for bioactive component recovery from date byproducts and waste.

Dates	Extraction	Treatment	Experimental condition	Highlights	Reference
Date powder (*Degla-Beida*)	Syrup	MAE + UAE	UAE: 42 kHz at 30, 40, 50, 60, and 69 °C for 15, 30, 45, 60, 90 min. MAE: 100, 300, 500, 700, and 900 W for 0.30, 0.45, 1, 2, 3, 4, and 5 min.	Under optimized conditions, maximum TSC recoveries for MAE and UAE were approximately 233.796 g/L and 202.037 g/L, respectively.	[86]
Roasted date seeds (*Kabkab*)	Bioactive components (phenolics, flavonoids, and condensed tannins)	MAE + UAE	MAE: 400 W for 5 min. UAE: amplitude of 80 % (40 kHz, 500 W, 25 °C) for 30 min. UAE + MAE: UAE for 15 min then MAE for 2.30 min.	UAE had the best and MAE the worst phytochemical yield. MAE's low yield was achieved in less than 5 min.	[34]
Date seed powder (*Khalas*)	Bioactive components	NADES (Acetic acid, citric acid, lactic acid, and malic acid) + UAE	NADES: molar ratios (1:1, 1:2, 1:3, 2:1, 3:1). NADES solid-to-solvent ratios (1:20, 1:30, 1:40, 1:50, and 1:100 g/ml) + UAE: 80 % amplitude for various extraction times (10–50 min) at 60 °C.	The highest extraction efficiency was achieved with NADES containing a single carboxylic acid functional group, in the order: lactic acid > acetic acid > citric acid > malic acid. NADES with multiple functional groups (citric and malic acid) retained more bioactive compounds (TPC) during storage at − 20 °C and 4 °C and maintained their extraction potentials better than those with a single functional group.	[130]
Date seed powder (*Khalas*)	TPC and antioxidant activity	NADES (choline chloride, lactic acid, citric acid, glycerol, and fructose) + UAE	NADES: (20 % water) + UAE: US bath at 40 °C for 30 min.	NADES with lactic and citric acid demonstrated high extraction efficiency for TPC and DPPH compared to conventional solvents. Moreover, citric acid and glycerol extracts contained the highest catechin concentration.	[131]
Date seed powder (*Khalas*)	Bioactive components	NADES + UAE	NADES content (30 %, 50 %, and 70 %), and solid-to-solvent ratio (1:30, 1.5:30, and 2:30 g/mL), sonication amplitude (70, 80, and 90 %) for 10, 20, and 30 min.	Lactic acid-based NADES had the highest extraction efficiency, and combining them with UAE recovered more phenolic compounds, such as 3,4-dihydroxybenzoic acid, catechin, and caffeic acid.	[87]
Date seed powder (*Khalas*)	Bioactive components	NADES (choline chloride-lactic acid or xylose) + MAE	NADES: percentage solvent contents (25, 55, and 85 %) + MAE: 600 W, at 20, 55, and 80 ℃ for 5, 12.5, and 20 min.	Under optimal conditions, the highest FRAP, DPPH, and TPC values were 771.54-, 734.34-, 503.75, 396.73 mM TE/g powder, and 147.92, 234.65 mg GAE/g powder for lactic acid and xylose. Catechin, 3,4-dihydroxybenzoic acid, and caffeic acid were the main phenolic compounds in the extracts.	[132]
Date palm leaves powder (*Khalas*)	Bioactive components	NADES (glycerol, oxalic acid, citric acid, malic acid, xylose, glucose) + MAE + UAE	NADES + water at 10, 20, 40, and 80 %. NADES + UAE: NADES dilution (30 % and 60 % with water), US power (40 W and 60 W), and treatment time (30 and 60 min). NADES + MAE: NADES dilution (30 % and 60 % with water), microwave power levels (400 W and 800 W) and treatment time (0.5 and 2 min), at 40 ℃.	Glycerol-based NADES yielded more phenolics than saccharide and organic acid-based NADES. While UAE-NADES was ineffective in enhancing phenolics recovery, MAE-NADES proved significantly effective.	[133]
Date seed powder (*Khalas*)	TPC	Polyol-based NADES + (HAE or MAE or UAE)	NADES with 20 % water. HAE: solid-solvent ratio of 1:30 (g/ml), 10,000 rpm for 5 min. MAE: solid-solvent ratio of 1:30 (g/ml), 600 W at 50 °C for 10 min. UAE: solid-solvent ratio of 1:30 (g/ml), 80 % amplitude at 50 °C for 50 min.	Among the five NADES tested, choline chloride: ethylene glycol (ChCl: Eg) showed the highest efficiency for extracting date seed phenolic compounds. Using ChCl: Eg, the maximum extraction efficacy was observed with MAE, followed by HAE and UAE. Notably, the binary hybrid techniques combining UAE and MAE (UMAE), and HAE and MAE (HMAE) significantly increased the recovery of bioactive compounds, with 52 % and 49 % higher TPC, respectively, compared to single extraction techniques.	[20]
Date palm fruits	TPC and TFC	NADES (lactic acid and sucrose) + UAE	NADES: molar ratio of 3:1 + UAE: 130 W, 20 kHz.	The tested fruit cultivars exhibited substantial variations in antioxidant composition, with Ourous cultivar having the highest TPC and TFC (1288.7 mg GAE/100 g DM and 53.8 mg QE/100 g DM, respectively) among all cultivars.	[134]

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Table 2 (*continued*)

Dates	Extraction	Treatment	Experimental condition	Highlights	Reference
Date palm fruit (*Ourrous* and *Ouksaba*)	TPC and antioxidant activity	NADES (lactic acid and sucrose) + UAE	Solvent concentration (0–100 %) sample/solvent ratio (100/15 to 300/15 mg/mL) for 3–40 min.	Double extraction with lactic acid/ sucrose (3:1) at 100 % concentration, 100 mg/15 ml sample/solvent ratio, 40 min yielded the highest TPC (1393.5 mgGAE)/100 g and best antioxidant activity (948.1 mgAAE)/100 g.	[91]
Date seeds	Polysaccharides	NADES (choline chloride and ethylene glycol) + UAE	NADES: 10 % water + UAE: time (5, 12.5, 20 min) and amplitude (40, 60, 80 Hz).	UPS exhibited a concentration-dependent enhancement in radical scavenging and antioxidant capabilities, with DPPH and ABTS activities rising from 23.1 % to 61.9 % and 21.8 % to 76 %, respectively, as concentration increased from 125 to 1000 µg/mL. Antioxidant potential also grew with UPS concentration, peaking at 627 µg/ mL (FRAP), 998 µg/mL (TAC), and 353 µg/mL (RP) at 1000 µg/mL.	[135]
Date pomace	Polysaccharides	NADES (Choline chloride with citric acid) + UAE	NADES: 1:1 M ratio with 30 % water + UAE: probe with 80 m amplitudes for 15 min.	Antioxidant assays (250–1000 mg/L of UPS) demonstrated dose-dependent activities, with US showing remarkable antioxidant activities and scavenging abilities between 59 to 82 % at 1000 mg/L.	[136]
Date fruit powder (*Sukkari*)	Sugar	NADES (choline chloride with oxalic acid, citric acid, gallic acid, ethanolamine, triethylene glycol, and water) + UAE	UAE: bath with settings of 45 kHz and 12 W/L, liquid-to-solid ratios (10 to 40 mL/g), sonication power of 6 W/L, at 30 and 70 °C for 20–60 min.	The synthesized NADES mixture with citric acid, and water (1:1:1 with 20 wt % water) achieved the highest sugar yield of 78.30 ± 3.91 g/100 g, outperforming conventional solvents like water (29.92 ± 1.50 g/100 g). Optimization further increased sugar recovery to 87.81 ± 2.61 g/100 g under conditions of 30 °C, 45 min, and a solvent to solid ratio of 40 mL/g. Comparing NADES-UAE with conventional hot water extraction (61.36 ± 3.06), the former showed a 43.1 % higher sugar yield.	[137]
Date palm fruit extract (*Sukkari*)	Bioactive components	PEF-assisted ethanolic extraction	1, 2, and 3 kV/cm, 10 Hz for 100 µs, pulses number: 30.	PEF (3 kV/cm) increased carotenoids, anthocyanins, flavonoids, and phenolics. It also increased volatile components.	[79]
Downgraded fresh date palm fruit (*Allig*)	TPC, antioxidant activity, and phenolic profiles.	PEF-assisted ethanolic extraction	50 % methanol, 30 Hz, time: 50 µs, pulse number: 240, at 1, 2, and 2.5 kV/cm, at 20, 40, 50 °C	PEF-assisted extracts at 2.5 kV/cm and 50 °C demonstrated a 27 % increase in TPC and a 31 % boost in antioxidant activity, with improved phenolic profiles compared to untreated extracts. PEF treatment significantly enhanced bioactive components and antioxidant activities in date fruits, irrespective of treatment type and extraction temperature.	[138]
Date seed powder (*Khalas*)	Nanoparticles	MAE	0.5 kW, methanol concentration (80 %), and solid/water ratio of 40/ L (w/v).	Seed nanoparticles had improved TPC, TFC, and antioxidant activities. Major phenolic compounds were 3,4-dihydroxy benzoic acid, ferulic acid, and p-coumaric acid.	[83]
Dates powder (*Degelt Nour*)	TPC and antioxidant activity	Ultrahigh-pressure–assisted extraction	Ethanol concentration (0–100 %), liquid/solid ratio (10–70 mL/g), 100–600 MPa at 25–65 °C.	Ultrahigh-pressure impacted extraction yield. Optimal conditions were 60.54 % ethanol, 70 mL/g solvent-to-sample ratio, 65 °C temperature, and 600 MPa pressure.	[73]
Ground date seed (*Sukari*, *Ambara*, *Majdool* and *Sagai*)	Bioactive components	SC-CO_2 and Subcritical CO_2	SC-CO_2: Ethanol (30 %), 35–70 °C, 15–40 MPa, and CO2 flow rate was kept 0.5–5 mL/min. Subcritical CO_2 extraction: The number of extraction cycles for each sample was 250 (approx. 12 h) at a pressure of 6.8 MPa and temperature of 29 °C.	In vitro antioxidant tests showed promising results (13.42–23.83 µg AAE/mL), antiradical (228.76–109.69 µg/mL DPPH IC50), ferric reducing antioxidant power (1.43–2.10 mmol TE/100 g) and ABTS cation scavenging (375.74–717.45 µmol TE/ 100 g) compared to Soxhlet extracts.	[6]
Date fruit flesh extracts (*Sukari*, *Ambara*, *Majdool*, and *Sagai*)	Bioactive components	SC-CO_2 and Subcritical CO_2	SC-CO_2: 52.5 °C temperature, 27.50 MPa pressure, 5 mL CO_2/min flow rate) and subcritical (SubCO_2, 250 extraction cycles, 29 °C temperature, 6.8 MPa, 12 h, ethanol solvent).	Supercritical fluid extraction yielded the most extracts, while SubCO_2 produced more phytochemicals. SubCO_2 was the top method and Majdool was the best date variety for both phytochemicals and biological properties.	[74]

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Table 2 (*continued*)

Dates	Extraction	Treatment	Experimental condition	Highlights	Reference
Date palm leaves	Cuticle wax	SC-CO_2	40 °C to 100 °C and pressure (80 bar to 400 bar). The CO_2 flow rate was set at 40 g/min.	Date palm leaves yielded 3.49 % wax. Date palm wax had good gelling and high thermal stability compared to other waxes.	[18]
Date fruit (*Barhe*)	Reducing sugars and other nutrients	SWE	10–30 bar, 100–130 °C for 5–15 min, and solvent-feed ratio (5–15 mL/g).	Microwave-pretreated fruit pulp yielded a maximum of 69.67 g/100 g at 37.5 bars, 130 °C, 11 mL/g, and 11 min. This condition also resulted in an 81 % recovery efficiency for reducing sugars.	[76]
Date fruit (*Barhe*)	Sugar	SC-CO_2	6.77 wt% water mixed CO_2 solvent system at 308 bar, 65 °C, and CO_2 flow rate of 31,000 kg/h.	The process achieved 99.1 % efficiency in extracting reducing sugars from dates, enhancing the solubility of date sugar powder by eliminating insoluble fibers and adding Gum Arabic. The final product's solubility was 0.89 g/g water.	[75]

Abbreviations: UAE: Ultrasound-assisted extraction; MAE, microwave-assisted extraction; PEF: Pulsed electric field; NADES: Natural deep eutectic solvents; HAE: homogenization-assisted extraction; SC-CO2: Supercritical carbon dioxide; SWE: Subcritical water extraction; TPC: Total phenolic content; TFC: Total flavonoid content; DPPH, 1-diphenyl-2-picrylhydrazyl; FRAP: Ferric reduction ability; UPS: Ultrasonically extracted polysaccharides.

proanthocyanidin content increased linearly up to 54.57 % ethanol concentration. Whereas the most effective concentration for extracting high-quality phenolic compounds, as indicated by the antioxidant (DPPH inhibition %) activity, was found at 95 % ethanol concentration. Optimal TFC and antioxidant activities were observed at a 70 % ethanol concentration. However, the extraction yields diminished at temperatures exceeding 150 °C, likely because of thermal degradation of the bioactive components within the date pits [48]. Additionally, longer extraction times and higher feed mixture concentrations positively influenced extraction yields, with more pronounced effects at lower temperatures and concentrations.

SC-CO_2 extraction demonstrated higher TPC, TFC, and total anthocyanin content (TAC), whereas SFE was more efficient in extracting total carotenoid content (TCC) from date seeds [6]. However, the levels of TAC and TCC were dependent on the type of date and specific extraction parameters. Moreover, sub-CO_2 extracts exhibited the most potent antioxidant properties among the methods compared. However, the efficiency of the SFE method is significantly influenced by the operational temperature and pressure, which affect the yield.

The application of ethanol as a co-solvent in both SC-CO_2 and SFE techniques demonstrated a more environmentally friendly approach than traditional Soxhlet extraction using *n*-hexane. Additionally, it was noted that low-temperature treatments in both SFE (57.5 °C) and sub-CO_2 (29 °C) were more effective in extracting phenolics (including anthocyanins and flavonoids) and carotenoids from dates, while maintaining the integrity of these compounds [74]. This investigation sheds light on the significance of selecting the appropriate date variety for enhancing the extraction of phenolics from dates and their byproducts. Majdool date flesh extract was found to possess a higher concentration of bioactive compounds and exhibited increased antioxidant properties compared to other date varieties, underlining the importance of varietal selection in achieving optimal results [74].

2.2.2. Extraction of reducing sugars

Extracting reducing sugars, including glucose and fructose, from date palm fruits is another area where SC-CO_2 shows significant potential [75]. The efficiency of the method was influenced by the flow rate of the SC-CO_2, with an optimal flow rate of 31,000 kg/h, achieving a recovery of 99.1 % of reducing sugars when using water concentration of 6.77 % wt. To achieve the optimal extraction of glucose and fructose, the desired water flow rate was found to be 2100 kg/h. Simulations of the supercritical process indicated that the peak product flow of glucose and fructose occurred at a pressure of 308 bar with an optimal temperature of 65 °C for the extraction stage. According to the authors, pressure and temperature have a significant impact on the glucose and fructose yields during the extraction process [75].

SWE is significantly more effective than traditional hot-water extraction in terms of both the extraction and recovery rates of these sugars [76]. The SWE achieved an 81 % recovery rate, which is nearly two and a half times higher than that obtained using conventional methods. Furthermore, the efficiency of the SWE extract was found to be 43 % greater than that of the traditional hot water extraction. The highest yield of reducing sugars was achieved at 37.5 °C, 130 °C, and 11 min with a solvent-feed ratio of 11 mL/g, resulting in a yield of 69.67 % of fruit pulp. Additionally, the SWE method demonstrated a 55 % enhancement in total flavonoid contents (TFC) compared with conventional hot water extraction, highlighting its potential for the extraction of valuable compounds from date palm fruits.

3. Other emerging techniques for the sustainable green extraction processing of bioactive compounds from date palm byproducts

In recent years, the exploration of innovative extraction techniques has gained momentum, with the aim of enhancing the recovery of valuable bioactive compounds from date palm byproducts with minimal environmental impacts [77]. Among these, PEF, MAE, and NADES have shown promise, owing to their efficiency and sustainability (Table 2). The selection of an appropriate extraction method for large-scale applications depends on multiple factors, including throughput, equipment requirements, energy consumption, and automation potential. To provide a comprehensive comparison, Table 3 summarizes the key characteristics of various emerging extraction techniques, highlighting their advantages and limitations in an industrial setting. This comparative analysis serves as a practical guide for researchers and industries aiming to optimize extraction efficiency based on specific operational needs.

3.1. Pulsed electric field-assisted extraction

The PEF technique is particularly effective for extracting phenolics and flavonoids from date palm waste. Research has indicated that PEF not only conserves time and energy but also serves as an effective pretreatment technique [78]. Date fruit extracts subjected to PEF technology at varying electric field strengths (1, 2, and 3 kV/cm, with pulse durations of 10 s) exhibited significant enhancements in TPC (67.35 mg GAE/100 g), TFC (6.75 mg CE/100 g), and TAC (2.08 mg/L) compared to untreated extracts [79]. Furthermore, PEF treatment at high voltages enhanced the content of TCC, anthocyanins, flavonoids, and phenolics. For instance, the TCC values in the PEF-treated samples (at 1, 2, and 3 kV/cm) were 3.29, 4.93, and 6.10 μg/mL, respectively, exceeding the 2.85 μg/mL in the untreated extract. The PEF-treated

Table 3
Comparative analysis of emerging extraction methods for large-scale applications.

Factor	Ultrasound Extraction	Microwave Extraction	NADES Extraction	Pulsed Electric Field Extraction	Supercritical Fluid Extraction
Throughput	Medium to High – can be scaled up with multiple reactors	Medium to High – continuous flow systems available (limited by vessel size)	Medium – can be challenging to scale up due to solvent viscosity	High – continuous processing is feasible; suitable for large-scale operations	Medium – limited by vessel size and pressure requirements; ideal for large-scale applications
Equipment Requirements	Requires ultrasonic probes or baths, which are relatively affordable and easy to maintain.	Specialized microwave generators and applicators	Simple – requires only basic mixing and heating equipment (similar to conventional solvent extraction setups)	Specialized pulse generators and treatment chambers	Complex – high-pressure pumps, vessels, and temperature control systems
Energy Consumption	Moderate – energy required for ultrasonic waves (depends on duration and power)	Moderate to High – depends on the material and microwave frequency	Low – primarily for mixing and heating (dependent on solvent recovery); NADES can operate at ambient conditions.	Moderate – depends on pulse parameters and field strength	High – energy intensive due to high pressure, solvent recycling (compression of CO_2) and maintaining supercritical conditions
Potential for Automation	High – easily integrated into automated systems with process control	High – can be fully automated with feedback control (batch or continuous processing)	Medium – automation of mixing and heating is possible but solvent handling can be complex (dependent on process design)	High – well-suited for continuous automated processing	Medium – automation is possible but requires sophisticated control systems
Extraction Efficiency	High – effective for heat-sensitive compounds	High – rapid extraction of polar compounds; limited for thermally unstable compounds.	Variable – depends on the choice of NADES and target compounds	High – enhances mass transfer and cell disruption; effective for enhancing extraction yield; best for liquid matrices;	High – selective extraction of non-polar compounds; excellent for high-value products; produces solvent –free high-purity extracts
Solvent Consumption	Low to Medium – can be optimized with process parameters	Low to Medium – can be efficient with optimized conditions	Low – often uses less toxic solvents	Low – can be used with minimal solvent or water	Low – uses supercritical fluids (e.g., CO_2) which can be recycled
Environmental Impact	Relatively low – can reduce solvent use and extraction time	Relatively low – can reduce solvent use and energy consumption compared to conventional methods	Low – uses biodegradable and non-toxic solvents; solvent recycling can be challenging	Low – minimal solvent use and low energy consumption	Low – uses recyclable solvents and can be highly selective
Cost	Moderate – relatively low equipment cost but may require maintenance	Moderate to High – higher equipment cost but can offer faster extraction	Low – low equipment cost and uses inexpensive solvents; throughput scalability requires optimization	Moderate to High – specialized equipment can be costly	High – high capital and operating costs due to complex equipment and high pressure. CO_2 recycling essential for economic feasibility
Reference	[38,139]	[140–142]	[94,131]	[143,144]	[67,70,119]

date samples also exhibited greater DPPH radical-scavenging activity than the untreated extract, with the most potent activity observed at 3 kV/cm (72 %). The PEF-assisted extraction method, which employs high-voltage and short electrical pulses, disrupts the cell walls and membranes to aid in the release of bioactive components. The application of MAE and PEF enhanced the speed and efficiency of oil extraction from black cumin seeds [80]. Whereas, the combined treatment of PEF and ultrasound achieved the highest value of flavonoids, phenolic, flavonols, anthocyanin, carotenoids, total chlorophyll, vitamin C, DPPH, and total antioxidant capacity of spinach juice [81]. The application of PEF under optimized conditions, such as specific electric field strength and pulse duration, can lead to a substantial increase in the yield of targeted compounds while also being energy-efficient and preserving the integrity of thermally labile bioactives [82].

3.2. Microwave-assisted extraction

Recent advances have introduced MAE as a potential alternative to conventional organic solvents. MAE is particularly useful when working with non-toxic solvents and when avoiding compound degradation is crucial. MAE utilizes microwave energy to heat the solvent and plant material, thereby facilitating the rapid extraction of bioactive compounds [83]. For example, MAE has been found to yield higher concentrations of flavonoids and phenolic compounds from orange peels compared to SC-CO_2 extraction [84]. The rapid heating and cooling cycles in MAE can enhance the extraction efficiency of these compounds by disrupting cell walls and facilitating the release of bioactive substances into the solvent [85]. As water evaporates, the binding between tissues and molecules is disrupted, leading to the rupture of cell walls and liberation of cellular material (Fig. 5a, b). This method has demonstrated its capability to extract a wide range of compounds, including antioxidants and phenolics, from date palm byproducts, with the advantages of reduced extraction time and solvent usage (Table 2). For instance, *Degla-Beida* date powder yielded a maximum total soluble content of approximately 233.796 g/L under optimized conditions, outperforming conventional extraction methods in terms of speed and yield [86]. Similarly, *Khalas* date seed powder, when combined with NADES, achieved significant recoveries of phenolic compounds such as catechin and caffeic acid, highlighting the technique's capability to extract diverse bioactive molecules [87]. However, in certain cases, MAE's yield was relatively lower than alternative methods. For example, roasted date seeds (*Kabkab*) exhibited the lowest phytochemical yield under MAE compared to UAE, although the extraction was completed in less than 5 min [34]. This indicates that while MAE is highly time-efficient, its performance may depend on the specific matrix and target compounds. The optimal microwave power and extraction time are crucial parameters that need to be fine-tuned to maximize the extraction efficiency while preventing the degradation of sensitive molecules [88].

3.3. Natural deep eutectic solvents based extraction

NADES, a new class of eco-friendly solvents, has emerged as a potent medium for the extraction of bioactive compounds [89,90]. NADES can efficiently solubilize plant bioactive compounds at mild temperatures by forming a eutectic mixture of natural compounds (such as choline chloride and organic acids), offering a sustainable alternative to conventional solvents [87]. NADES effectively solubilizes phenolic acids,

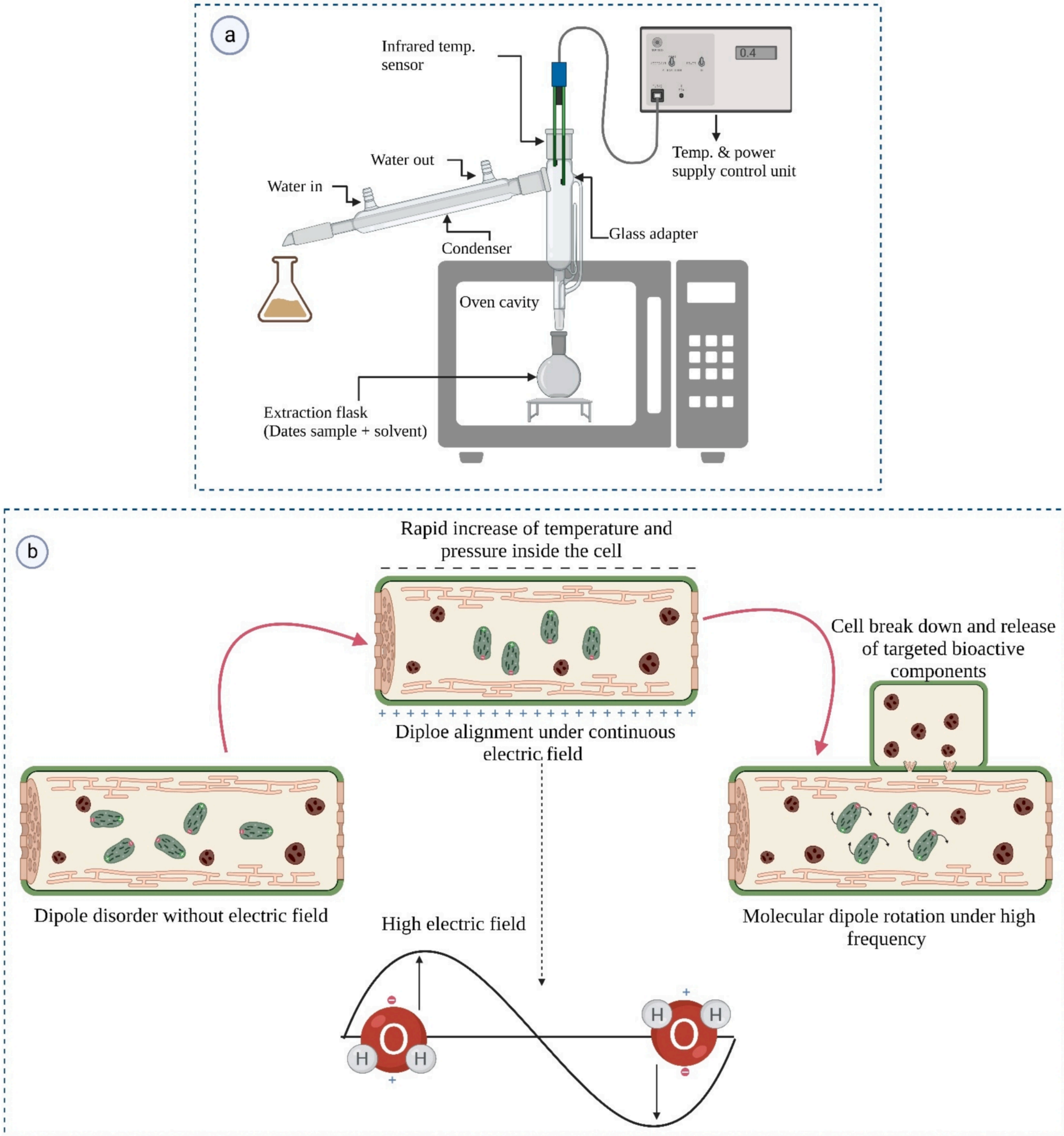

Fig. 5. (a) Illustration of the experimental procedure for the microwave-assisted extraction system (b) Mechanism of the microwave-assisted extraction.

flavonoids, and other bioactive compounds due to its high polarity and compatibility with natural compounds (Fig. 6). The efficacy of NADES, particularly those based on carboxylic acids, sugars, and polyalcohols, has been evaluated in TPC and TFC extraction from date seeds [87]. Carboxylic acid-based NADES were found to be the most efficient for TPC recovery, whereas those based on carboxylic acids and polyalcohols showed the best TFC recovery and exhibited commendable antioxidant activity. NADES based on carboxylic acids and polyalcohols showed the best TFC recovery and good antioxidant activity compared to conventional solvents, such as 80 % ethanol and 80 % methanol. The combination of NADES with UAE and MAE enhances extraction efficiency and shortens extraction time [87,91,92]. NADES-based extraction techniques offer several advantages including lower energy requirements, reduced emissions, and improved sustainability [89,93]. These findings highlight the potential of innovative extraction methods to enhance the sustainability of the food industry, contribute to a circular bioeconomy, and reduce the environmental footprint of food production [19,94].

4. Life cycle assessment and sustainability benefits of emerging extraction techniques for a circular food bioeconomy, environmental impact, and energy efficiency

The transition towards sustainable extraction methods from food

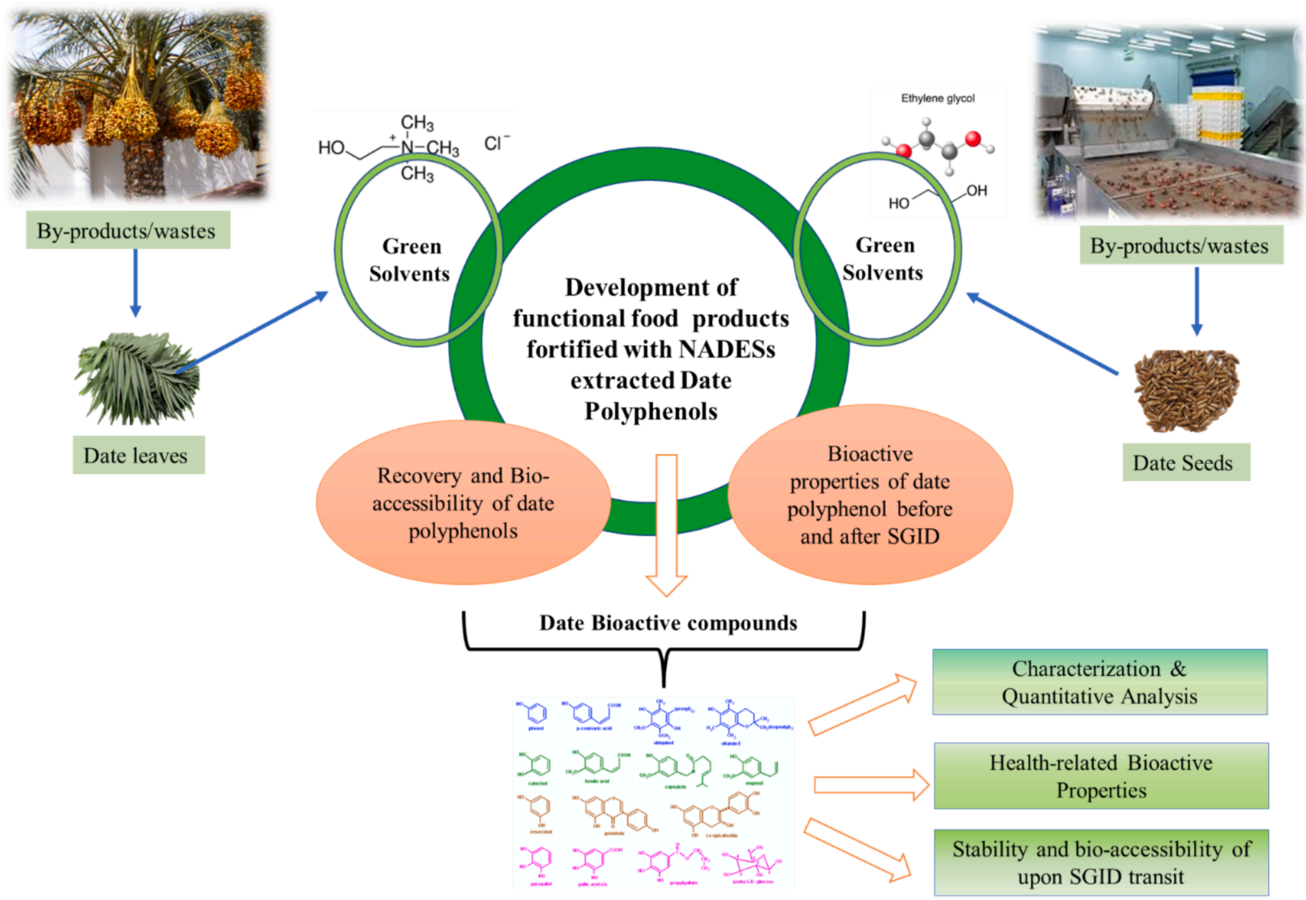

Fig. 6. Natural deep eutectic-based green solvents for the extraction of bioactive compounds from date by-products.

industry byproducts, such as date palm waste, is pivotal in advancing the circular bioeconomy. Consumer demand for natural and organic products produced without harsh processing methods or synthetic chemicals is increasingly shaping the circular bioeconomy within the food industry [95]. This change not only meets market demands but also aligns with SGDs [96]. The principles of a circular economy emphasize efficient resource utilization and waste minimization, aiming to create a closed-loop system that promotes the reuse and recycling of by-products [97]. In the case of date palm by-products, these materials can be converted into new value-added products instead of being discarded as waste (Fig. 3) [98]. For example, phenolic compounds extracted from date seeds can be utilized to develop antioxidant-rich foods, whereas the remaining biomass can be processed into biofuels, biopolymers, and other bioproducts [34,99]. Extracted bioactive compounds have the potential to be incorporated into functional foods with targeted health benefits, paving the way for new date-based nutraceuticals and dietary supplements [100]. Utilizing date by-products can help reduce waste and conserve resources, while integrating waste valorization with existing processing facilities could lead to biorefineries capable of producing high-value products, such as biofuels and bioplastics [13,83]. Further research on the properties of the extracted fibers and biochar from date palm waste could unlock their potential for use in advanced materials, such as bio-composites for construction, packaging materials, and components for 3D printing [101,102]. While the extraction of bioactive compounds such as antioxidants and phenolics from date palm byproducts is well-documented, studies exploring the recovery of pigments, proteins, and fats remain limited, presenting an opportunity for future research.

In food production, adopting non-conventional extraction techniques is crucial for reducing greenhouse gas emissions and advancing the circular economy [28,103]. However, direct comparisons of the energy consumption across these techniques are limited. Life cycle assessment (LCA) is a comprehensive tool for evaluating the environmental impacts of various extraction methods, considering energy consumption, waste generation, and resource utilization. Recent studies have underscored the significance of LCA in assessing the sustainability of extraction techniques such as UAE, SFE, MAE, and traditional methods [104]. For instance, an LCA conducted by Luna et al. [105] highlighted trade-offs between extraction efficiency and environmental sustainability, suggesting that the UAE offers a viable alternative to balance these factors. Another study comparing extraction processes for polyphenols from spruce bark indicated that electricity use for heating significantly impacted the environmental profiles of the assessed methods, including UAE [106]. Although UAE demonstrated lower environmental impacts across all categories, producing only 8 kg CO_2 equivalent per gram of polyphenols, it had a slightly lower TPC yield than sodium hydroxide extraction [106]. Nevertheless, its environmental impacts were approximately 20 % of those associated with sodium hydroxide extraction.

Energy audits further enhance this analysis by detailing the energy-consumption patterns of each method. By quantifying the carbon footprint and energy usage per unit of the extracted compound, tangible metrics can be established for sustainability comparisons. For example, research on the environmental impact of five extraction technologies for polyphenols from *Moringa oleifera* leaves revealed that UAE had a lower overall environmental burden than traditional methods, primarily due to reduced electricity consumption and solvent use [107]. Unlike conventional methods, such as boiling water and maceration, UAE is more efficient and environmentally friendly, contributing to lower ecotoxicity and toxicity levels [107]. Moreover, studies have shown that UAE can extract bioactive compounds more efficiently while requiring less energy and solvent than conventional methods [108–110].

Research has also explored the combination of UAE and MAE to optimize the recovery of bioactive components from date by-products [34,86,87] (Table 2). Both techniques are recognized for their lower energy requirements and reduced emissions compared to traditional thermal methods [104,111]. Furthermore, LCA results of polyphenols from downgraded beet seeds indicated that both UAE and MAE have distinct environmental impacts, with MAE showing higher ozone depletion potential due to equipment use, while UAE had longer extraction times, affecting energy consumption [112]. While nonthermal techniques offer numerous benefits for the extraction of bioactive compounds from date palm byproducts, scaling up these techniques to an industrial scale presents several challenges. The uniform distribution of ultrasonic waves or microwave energy in larger volumes can be difficult to achieve, potentially resulting in uneven extraction efficiency [113]. This issue arises due to the inherent characteristics of these energy forms, which can result in hotspots or uneven energy distribution. However, various strategies and techniques have been developed to address these challenges and improve extraction efficiency [114]. For example, the design of ultrasound transducers can significantly impact the distribution of acoustic energy. Different geometries can be used to achieve more uniform acoustic fields, thereby enhancing extraction efficiency [115]. Additionally, the high initial investment costs for industrial-scale equipment and the need for specialized training and maintenance can be barriers for widespread adoption [116,117]. Addressing these challenges through technological advancements and cost-effective solutions will be crucial for the successful industrial application of these sustainable extraction methods.

Emerging eco-friendly extraction methods, such as SFE, are designed to minimize environmental impacts by reducing harmful solvent residues and enhancing recyclability [118]. SFE is particularly effective for extracting sensitive compounds, such as thermolabile proteins, flavonoids, essential oils, and antioxidants, which may degrade at high temperatures [119–121]. These advanced green extraction technologies not only improve yield and selectivity but also enhance the quality and safety of extracts while conserving time and resources [79,83]. The unique properties of SFE, such as its low viscosity and high diffusivity, contribute to its effectiveness and lower environmental footprint compared to traditional methods [122]. A notable study compared supercritical CO_2 extraction with solvent extraction for producing β-carotene from microalgae (*Dunaliella salina*), analyzing the impacts of global warming and resource use. The LCA results indicated that the supercritical CO_2 process had a lower energy consumption and greenhouse gas emissions than the solvent-based method. However, the supercritical method yielded less β-carotene, necessitating higher nutrient inputs, which increased the toxicity-related effects associated with organic solvent extraction. Consequently, the cost of β-carotene is significantly higher (twice as much) when using the supercritical extraction process, suggesting that environmental benefits do not outweigh the economic drawbacks [123]. Many green extraction methods that use these solvents require less energy for heating and solvent recovery. For instance, supercritical water extraction operates at high temperatures but can effectively extract polar compounds with minimal energy use compared to traditional methods [122]. However, these methods remain an area of research, specifically for the extraction of bioactive chemicals, including polyphenols, flavonoids, and antioxidants, from dates.

The use of NADES for polyphenol extraction exemplifies how innovative methods can be assessed for their sustainability through LCA [124]. A study focusing on the sustainability of polyphenol extraction procedures from dark chocolate using NADES employed LCA methodology for various impact categories, such as greenhouse gas emissions, resource depletion, and potential toxicity, demonstrating the overall ecological benefits of NADES [124]. The analysis also correlated the sustainability of the extraction methods with the radical scavenging activity of the extracted compounds. Higher antioxidant activities indicate not only the effectiveness of the extraction process but also the potential health benefits of the bioactive compounds obtained through sustainable methods. Despite these advancements, there remains a lack of studies focusing on LCA in the context of date by-products. Future research should aim to quantify sustainability metrics across various extraction scenarios to establish a robust framework for assessing eco-friendly options for the recovery of bioactive compounds.

The adoption of UAE and PBE technologies for the recovery of bioactive compounds from date palm byproducts aligns directly with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). These innovative, non-thermal, green extraction methods offer a sustainable alternative to conventional extraction processes by significantly reducing solvent use, energy consumption, and waste generation. For instance, ability of UAE to operate at lower temperatures and with fewer chemical solvents minimizes the carbon footprint and hazardous waste production, contributing to cleaner production practices and efficient use of resources [25,28]. Similarly, PBE methods, including SFE, avoid the use of toxic organic solvents and operate under conditions that preserve the integrity of heat-sensitive compounds and promote the production of high-quality, sustainable food ingredients [71]. By enhancing the extraction efficiency and yield of valuable antioxidants and phenolic compounds from date palm waste, these technologies also support the valorization of agricultural byproducts, thereby reducing food waste and promoting circular economic principles within the food industry. Such advancements not only contribute to environmental sustainability, but also offer economic benefits by creating new opportunities for the valorization of date palm byproducts, aligning with the global agenda for sustainable development.

5. Conclusion and future research prospectus

The exploration of non-thermal and green extraction methods, specifically UAE and SFE, for the valorization of date palm byproducts underscores a pivotal advancement towards fostering a sustainable and circular food bioeconomy. SC-CO_2 extraction stands out for its selectivity and ability to produce high-quality extracts with minimal environmental impact. It is particularly effective for extracting lipophilic compounds and certain vitamins, while UAE and MAE are more suitable for polar compounds and thermolabile substances. The choice of extraction method should be guided by the specific bioactive compounds of interest and the desired purity and quality of the final extract. These innovative extraction techniques not only offer a superior alternative to conventional methods by enhancing extraction efficiency and reducing solvent use but also significantly diminish the extraction time. The findings of this study highlight the potential of leveraging date palm waste, a substantially underutilized resource, to extract valuable bioactive compounds, including phenolics, flavonoids, and carotenoids, which exhibit promising antioxidant, anti-inflammatory, and antimicrobial properties. Furthermore, our study opens new avenues for integrating these advanced extraction methods with emerging technologies, such as NADES, MAE, and PEF to further augment the efficiency and sustainability of the extraction process. Such integration could potentially set new standards for the extraction industry, emphasizing low energy consumption, minimal environmental impact, and valorization of agricultural byproducts. By aligning with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), the findings of this study advocate for the adoption of sustainable practices in the food industry. They encourage the food industry to transition towards more eco-friendly extraction methods, which not only mitigate environmental impacts but also offer economic incentives by transforming waste into valuable products. In light of these findings, future research should focus on a comprehensive LCA of these green extraction techniques to thoroughly quantify their environmental benefits. Additionally, exploring the commercial viability and scalability of these methods could significantly contribute to their adoption in industrial applications, promoting broader objectives of waste minimization and sustainability within the global food industry.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Grammarly and Microsoft Copilot for language proofing and enhancement. The purpose of this tool was to improve readability, coherence, and language quality. Importantly, no new content was generated using this artificial-intelligence tool. Following the use of this service, the author(s) diligently reviewed and edited the content as necessary, thereby assuming full responsibility for the content of this publication.

CRediT authorship contribution statement

Ume Roobab: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Rana Muhammad Aadil:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation. **Shyam Sreedhara Kurup:** Writing – review & editing, Validation, Investigation. **Sajid Maqsood:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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