Review Article

Extraction and Encapsulation of Bioactive Components of Dates: A Bibliometric Analysis

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Abstract
This study provides a bibliometric analysis of one thousand publications total from the past decade concerning the extraction of bioactive compounds from date palm pulp and seeds and their encapsulation for functional food applications. The findings show that encapsulation technology plays a crucial role in enhancing physicochemical stability, improving bioavailability, and preserving bioactive compounds during processing. Several novelty gaps were identified: 1) bioactive compounds from tropical KL-1 date palm at the kimri stage have not been extracted using green solvents such as Natural Deep Eutectic Solvents (NADES) combined with ultrasound-assisted extraction; 2) the bioactive composition of KL-1 fruits and seeds at the kimri stage remains unknown; 3) the potential of kimri-stage KL-1 extracts as food ingredients and antioxidants has not been explored; and 4) their encapsulation to enhance the physicochemical stability of coconut skim milk has not been previously reported. The analysis also showed that spray drying, fluidized-bed drying, and foam-mat freeze drying are the most widely used microencapsulation methods for tamer-stage date extracts, typically employing carriers such as maltodextrin, gum arabic, hedysarum gum, and mangosteen gum, often blended with MCT oil. Overall, the results highlight promising opportunities to advance research on tropical date palm bioactives and their application as functional food ingredients.

Keywords: Bibliometric analysis, Date palm, Date seed, Food encapsulation

1 Introduction

The date palm (*Phoenix dactylifera* L.) is a fruit–bearing palm tree that is a member of the Arecaceae family. Its fruits, which are rich in carbohydrates, proteins, lipids, and vitamins, and contain many bioactive substances like phenolics, flavonoids, and carotenoids, are considered one of the most nutritionally valuable fruits [1], [2]. The fruits of the date palms are impacted by a host of factors, including cultivar, soil type, geographical location, and ripening stage [3], [4]. The ripening of the fruit occurs in five stages, which are Hababauk, Kimri, Khalal, Rutab, and Tamer [5], [6]. Some authors also mention a Biser intermediate phase between Khalal and Rutab, which could be more than one stage [7].

Worldwide, more than five thousand date palm cultivars are cultivated, with total fruit production exceeding 9.66 million metric tons in 2023. Approximately 10–15% of this yield consists of date palm by–products, particularly the seeds, which are estimated to account for 0.98–1.47 million metric tons annually [8], [9]. During the tamar stage, dates are mostly (approximately 70%) easily digestible sugars, with a low fiber content [3]. In addition to their wonderful nutritional value, dates also have great nutraceutical value, such as their protective antioxidant, antibacterial, antimutagenic, anti–inflammatory, hepatoprotective, anticancer, gastroprotective, and immunostimulatory potentials [4], [10], [11].

Antioxidants play a crucial role in lowering oxidative stress, preventing cellular damage, and reducing the incidence of chronic diseases like cancer and cardiovascular conditions by scavenging free radicals [12]. Due to their high levels of vitamins and polyphenolic metabolites, such as phenolic acids and flavonoid glycosides [13], dates harvested at the Kimri and Khalal stages of ripening are especially rich in antioxidants [4].

Research efforts have been disproportionately focused on the fully ripened Tamer stage, which is primarily used for sugar production, limiting insights into the bioactive potential of earlier stages, despite the fact that a strong correlation between antioxidant activity and total phenolic content in dates has been repeatedly demonstrated [14]. Furthermore, despite the abundant use, conventional extraction practices such as maceration, Soxhlet, and percolation place limitations on the value of low selectivity and low environmental burden. On the other hand, new green extraction methods like microwave–assisted extraction (MAE) [15] and ultrasound–assisted extraction (UAE) [16] have shown promise as alternatives. These methods make it easier to recover heat–sensitive bioactives while also encouraging environmentally friendly practices [17]. However, a major obstacle to using date–derived bioactives is their intrinsic instability. Due to enzymatic activity, oxidation, hydrolysis, pH variations, and thermal processing, these compounds are extremely prone to degradation [18]–[22]. Kaewchada and Chongcharoen [23] reported that vitamin E, a natural compound that is easily soluble in fat, is sensitive to light, heat, and exposure to oxygen, so packaging vitamin E is an effort to maintain the biological activity of vitamin E for various applications.

For example, it has been demonstrated that heat degradation of catechins dramatically reduces antioxidant functionality; autoxidation causes epigallocatechin gallate (EGCG) to decrease by as much as 40% at 120 °C. On the other hand, encapsulation, especially through nanoemulsion systems, can maintain bioactivity and enhance thermal stability throughout processing [24]. Because of its scalability, affordability, and suitability for both laboratory research and industrial–scale production, spray drying has become the method of choice among various encapsulation techniques [25]. It has significant financial advantages over freeze–drying since it eliminates the need for deep–freezing procedures and is 30 to 50 times more cost–effective [26]. However, important processing parameters such as the type of wall material used, the ratio of core to wall, and the applied drying temperatures strongly influence the final physicochemical quality and bioavailability of spray–dried encapsulates [27], [28]. Although the amount of research on date fruit bioactives is growing, there are still few thorough reviews that incorporate the following important factors: (i) the relative effectiveness of traditional versus cutting–edge polyphenol extraction techniques; (ii) encapsulation techniques to stabilise thermolabile antioxidants from dates; and (iii) the practical implications of these bioactives in food, cosmetic, and pharmaceutical applications.

By critically assessing recent developments in the extraction and encapsulation of polyphenols and flavonoids from dates, with an emphasis on underutilised ripening stages and by–products, the current review aims to close this knowledge gap. This work aims to inform research agendas, drive innovation in processing technologies, and promote the sustainable use of date pulp and seeds for the formulation of functional products that support global health and sustainability objectives by combining current insights with challenges and opportunities for the future. This method provides a systematic overview of the development of a scientific field, enabling the identification of influential research themes, key contributors, and gaps in the literature [29]. The purpose of this study was to cluster publications about the extraction of bioactive compounds from date pulp and seeds and conduct a bibliometric analysis. The analysis examined publication trends, keyword co–occurrence patterns, and collaboration networks to map the development and thematic evolution of the field. Because of its strong citation metrics and wide coverage of peer–reviewed literature, Scopus was chosen as the main database. Article titles, authors, affiliations, abstracts, keywords, publication years, and references were among the information that was obtained [29].

2 Methods

2.1 *Bibliometric analysis*

VOSviewer version 1.6.20, a popular tool for visualising co–authorship networks, keyword clustering, and citation relationships, was used to carry out the bibliometric mapping [30]. Bibliographic data was also managed and filtered using the Publish or Perish software. 582 articles were eventually included in the analysis from a starting pool of one thousand publications found using Scopus. Non–English documents, book series, and entries deemed outside the study's purview were eliminated as a result of the selection process's application of predetermined inclusion and exclusion criteria [31]. Non–English documents were excluded to maintain methodological consistency and ensure the reliability of bibliometric indicators, as Scopus and Web of Science predominantly index English–language publications with standardized metadata essential for accurate keyword extraction, citation analysis, and network mapping. However, we acknowledge that this criterion may limit the inclusion of region–specific studies, particularly from Arabic–speaking countries where date palm research is well established. This limitation is noted, and future reviews may integrate multilingual sources or employ translation–assisted text–mining approaches to achieve broader regional coverage [32].

This method provides a systematic overview of the development of a scientific field, enabling the identification of influential research themes, key contributors, and gaps in the literature [29]. The purpose of this study was to cluster publications about the extraction of bioactive compounds from date pulp and seeds and conduct a bibliometric analysis. The analysis examined publication trends, keyword co–occurrence patterns, and collaboration networks to map the development and thematic evolution of the field. Because of its strong citation metrics and wide coverage of peer–reviewed literature, Scopus was chosen as the main database. Article titles, authors, affiliations, abstracts, keywords, publication years, and references were among the information that was obtained [29].

By exposing understudied regions and new subjects, the bibliometric analysis also sought to identify research novelties. Trends in both traditional and unconventional extraction methods, as well as encapsulation technologies, were investigated using metadata from Scopus, Web of Science, other databases like ScienceDirect and Google Scholar. The terms "ultrasound–assisted extraction," "conventional extraction," "date palm," and "date seed" served as the search terms. To make sure the analysis included the most recent findings, the search was limited to publications published within the last ten years (2014–2024).

Strict criteria were used to select the included studies: only peer–reviewed journal articles that were specifically related to the extraction and encapsulation of date palm bioactive constituents were taken into consideration. Articles from journals that had ceased publication, non–original research (such as editorials or reviews unrelated to the subject), and studies that were not available through institutional subscriptions were among the excluded documents. The keyword co–occurrence network derived from articles indexed in Scopus, Web of Science, ScienceDirect, and Google Scholar between 2014 and 2024 is shown in Figure 3.

Date palm, *Phoenix dactylifera,* antioxidant activity, phenolic compounds, polyphenols, and green extraction were the six main thematic clusters found in the analysis. The prevailing research themes are reflected in these clusters, which also show growing interest in functional food applications and sustainable extraction technologies. The foundation for identifying research gaps and guiding future studies into the value-adding of date palm bioactives for innovations in food and health is provided by this bibliometric mapping.

2.2 *Research gap analysis*

In this paper, the primary focus is to identify existing research gaps in order to stimulate and guide future studies related to ultrasound–assisted extraction, conventional extraction methods, research involving date fruits and date seeds, as well as encapsulation technologies. Despite the growing number of studies in these areas, several critical gaps remain evident, particularly concerning methodological and research design limitations, as well as insufficient exploration of key research variables [33].

2.2.1 Identification of research domains

The research gap analysis was conducted by first classifying the selected literature into major thematic domains based on the research objectives, including raw material sources, extraction techniques, encapsulation methods, functional properties, and application fields. This classification enabled a structured comparison across studies and facilitated the identification of underexplored areas.

2.2.2 Comparative analysis of existing studies

A systematic comparative analysis was performed to evaluate similarities and differences among previous studies. Key parameters such as methodological approach, process efficiency, material characteristics, experimental conditions, and outcome indicators were examined. Studies were compared across different time periods, technologies, and application contexts to reveal patterns and inconsistencies in research findings.

2.2.3 Mapping of methodological and knowledge gaps

Research gaps were identified by mapping areas where:

(i) limited or inconsistent results were reported,

(ii) certain techniques or materials were underrepresented,

(iii) comparisons between conventional and emerging technologies were lacking, and

(iv) scalability, sustainability, or application-oriented evaluations were insufficient.

This gap mapping was supported by frequency analysis of keywords, methods, and performance indicators reported in the reviewed literature.

2.2.4 Evaluation of technological and application gaps

Technological gaps were assessed by analyzing the readiness level of reported methods, including process optimization, reproducibility, and industrial scalability. Application gaps were identified by examining the extent to which laboratory–scale findings were translated into real food systems, nutraceutical formulations, or pharmaceutical applications.

2.2.5 Temporal trend and evolution analysis

A temporal analysis was conducted to examine the evolution of research focus over time. Publication trends were analyzed to identify emerging topics and declining research interests, highlighting areas that require further investigation to advance the field.

2.2.6 Formulation of research opportunities

Based on the identified gaps, potential research opportunities were formulated by integrating scientific relevance, technological feasibility, and practical applicability. These opportunities were used to justify the novelty and significance of the present study.

2.3 ***Systematic review***

2.3.1 Literature search strategy

This systematic review was conducted using a systematic and structured approach to ensure the inclusion of relevant, high–quality, and up–to–date scientific studies. Peer–reviewed articles were collected from major international databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. The search was performed using combinations of keywords such as “bioactive compounds,” “extraction methods,” “encapsulation techniques,” “functional food,” and related terms. Boolean operators (AND, OR) were applied to refine the search and improve result accuracy.

2.3.2 Inclusion and exclusion criteria

The selection of articles was based on predefined inclusion and exclusion criteria. Studies were included if they:

(i) were published in peer–reviewed international journals,

(ii) were written in English,

(iii) focused on the extraction, characterization, or encapsulation of bioactive compounds, and

(iv) were published within the last 10 years to ensure scientific relevance.

Articles, such as conference proceedings, theses, book chapters, non–English publications, and studies lacking methodological clarity were excluded.

2.3.3 Study selection process

The initial search results were screened by reviewing titles and abstracts to remove duplicates and irrelevant articles. Subsequently, full–text articles were assessed for eligibility based on the defined criteria. The selection process followed a PRISMA–guided approach (Figure 1), ensuring transparency and reproducibility in article selection.

2.3.4 Data extraction and analysis

Relevant data were extracted from the selected studies, including authorship, publication year, raw material source, extraction or encapsulation method, key findings, and application potential. The collected data were systematically analyzed and synthesized to identify trends, technological advances, research gaps, and future perspectives in the field.

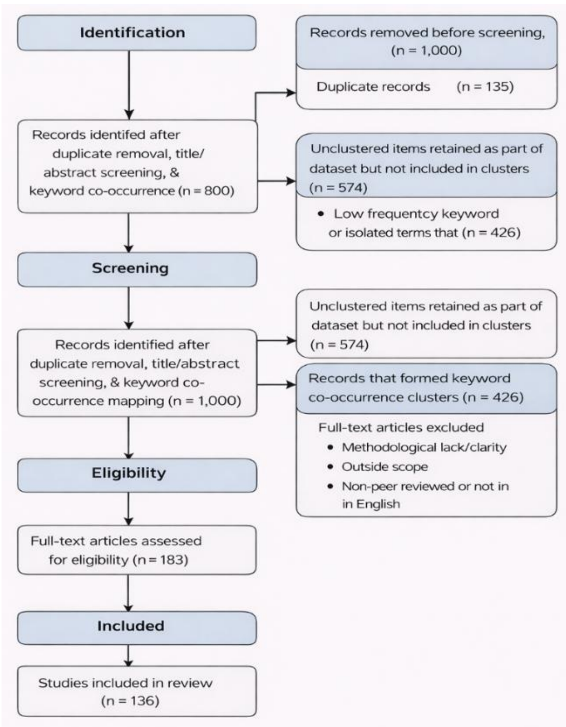

Figure 1: PRISMA flow diagram: systematic review and bibliometric analysis.

2.3.5 Synthesis of findings

The selected literature was qualitatively analyzed and categorized according to extraction techniques, encapsulation strategies, functional properties, and application in food systems. This narrative synthesis enabled a comprehensive comparison of methodologies and outcomes, providing a critical overview of current developments and challenges.

3 Results and Discussion

3.1 *Bibliometric analysis*

Keyword frequencies and the strength of their relationships are displayed in the co–occurrence map in Figure 2. Indicating the term's centrality to the research theme, the larger the node and label size, the more often the term appeared throughout the dataset. On the other hand, keywords with lower frequency and peripheral relevance are represented by nodes that are smaller or have a fainter colour.

The two most common terms, "phenolic compounds" and "antioxidant activity," had the biggest node sizes, indicating their dominance in the field. There is a substantial and established body of research linking these themes, as evidenced by the notable total link strength (TLS) of 93 for "date palm" and 79 for "antioxidant activity." 426 items that formed interconnected clusters out of the 1,000 documents." Specifically, it should be explained whether the remaining 574 documents were excluded from the clustering process or were simply categorized as unclustered items. Providing this clarification will improve the interpretability of the bibliometric coverage and help readers better understand the scope and limitations of the clustering analysis. Figure 3 illustrates how keywords have changed over time. More recent publications are represented by yellow–toned nodes in this map, with a focus on newly emerging subjects that were introduced in 2023–2024. A move towards sustainability, process optimisation, and value addition in food applications is indicated by the use of keywords like "green extraction techniques".

Each circle's diameter in the visualisation represents the frequency of a keyword; larger circles indicate more frequent occurrences, while smaller circles indicate less frequent ones. Encapsulation, antioxidant, stability, box–behnken design, and glucosyl hydrolase are the five components that make up the red cluster, for instance. Understudied but potentially important topics can be identified thanks to the density visualisation in Figure 4. Nodes that are faintly coloured, smaller, and farther from the cluster centre suggest that there has been little research done on them, which could lead to new discoveries and more study. "Ultrasound–assisted extraction," "green extraction techniques," "bioactive substances," "encapsulation," "deep eutectic solvents," "box–Behnken design," "biocompatibility," "nanoemulsion," "bioaccessibility," and "chlorogenic acid" are a few examples of such emerging or niche keywords. These subjects are at the map's edge, indicating that they require more research and development. Notably, phrases like "cosmo–RS prediction," "artificial neural network," and "response surface method" imply that computational modelling and predictive analytics should be incorporated into the design of the extraction process. These findings show how precision methods and interdisciplinary approaches are becoming more and more popular.

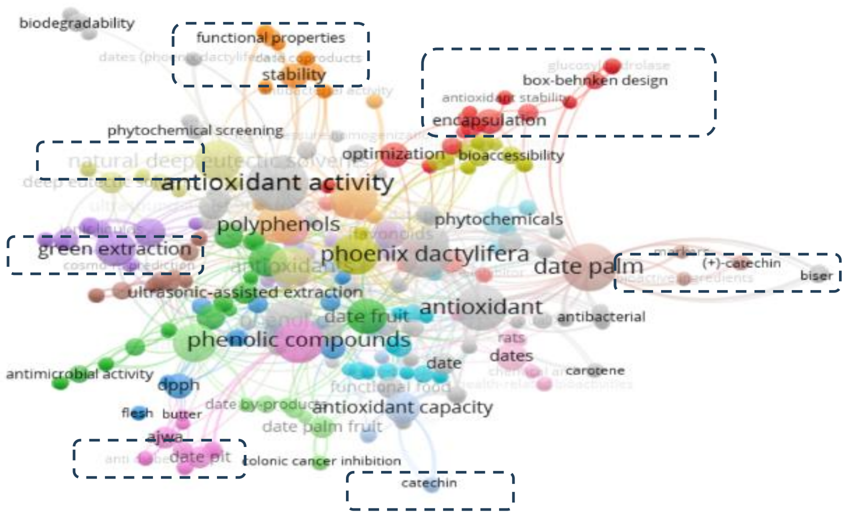

Figure 2: The clusters co–occurrence map with different colors.

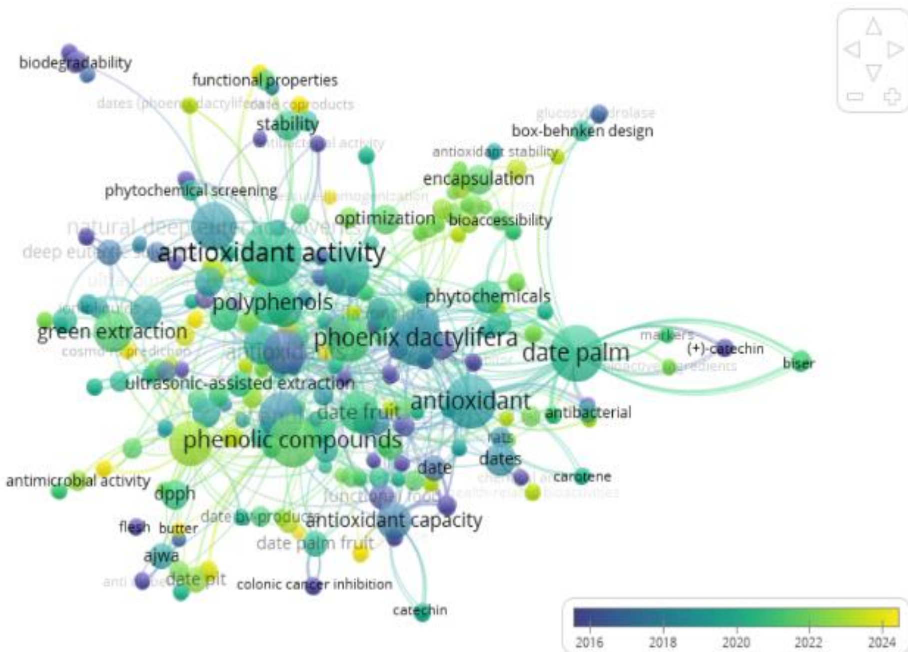

Figure 3: The clusters of the keywords ‘extraction’, ‘date palm’, and ‘date seed’ contained in the Scopus, WoS, Google Scholar databases in 2014–2024 (The overlay visualization).

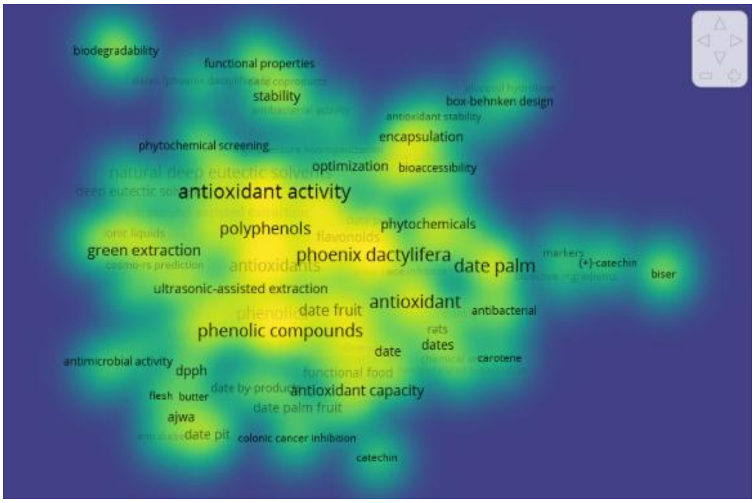

Figure 4: The density visualization.

The inclusion of COSMO–RS prediction and artificial neural networks highlights the growing role of computational tools in guiding extraction process design, as these methods enable the prediction of solute–solvent interactions, estimation of extraction efficiencies, and identification of optimal processing conditions with minimal experimental effort. COSMO–RS provides molecular–level insight into solvent suitability, while ANN models capture complex nonlinear relationships among extraction parameters to support accurate process optimization. Briefly clarifying these functions strengthens the rationale by demonstrating how such predictive tools can accelerate formulation decisions, reduce trial–and–error experimentation, and enhance overall process performance. It's interesting to note that very few cultivar–specific terms were found, including "Ajwa dates," "Deglet Noor," and "Biser" (referring to ripening stages). Tropical date cultivars like KL–1, on the other hand, were completely missing, suggesting a substantial research gap and the potential for novelty in regional date varieties, particularly in equatorial or Southeast Asian settings. Future research incorporating them could deepen our understanding of date bioactives in terms of geography and cultivar.

According to this bibliometric analysis, there is a great deal of space for new research even though a number of areas within the field of date palm bioactives are well–established, particularly about antioxidant compounds and traditional extraction methods. Research in areas like cultivar–specific studies, bioaccessibility and stability studies, and environmentally friendly extraction techniques is still lacking. Future research directions can be influenced by these findings, especially when it comes to creating sustainable processing technologies and novel food applications.

3.2 *Bioactive components of date pulp*

Date pulp bioactive ingredients are mostly extracted using different solvent systems. Table 1 summarises the conventional extraction process, which uses a methanol:water (4:1) solvent mixture [34]–[36]. Aqueous–based extraction techniques were used at temperatures between 30 and 90 °C, with shaking times of 0.5 to 6 hours and solid–liquid ratios of 100 to 500 mg/mL. Using 250 mL of acetone–water (4:1), Hamad *et al.*, [37] extracted phenolic compounds from 50 g of date fruit.

The rutab–phase dates pulp was extracted conventionally by Khalaf *et al.*, [37] using ethanol and acetone, and then concentrated using a rotary evaporator. Using HPLC, phenolic and flavonoid compounds were separated and identified. Overall, a conventional extraction technique was used; non–conventional methods are usually reserved for the tamar phase. Conventional extraction is typically employed; non–conventional extraction is typically limited to the tamar phase.

Table 1: Bioactive components of dates pulp.

Name of bioactive component		Composition dates pulp mg/100 g dry weight at harvest phase				Sources
		Kimri (1 Month)	Khalal (2 Months)	Rutab (3 Months)	Tamar (4–5 Months)	
Gallic Acid	Phenolic acid	*	19.97	14.5	13.97	[38], [39]
P–Cumaric Acid	Phenolic acid	*	1.52	2.07	3.09	[36], [40], [37]
Ferulic Acid	Phenolic acid	*	9.71	5.25	2.52	[36], [40], [37]
Protocatechuic Acid	Phenolic acid	*	*	12.5	1.21	[39], [40], [37]
Syringic Acid	Phenolic acid	*	3.19	5.74	0.82	[36], [40], [37]
Chlorogenic Acid	Phenolic acid	*	0.71	4.75	0.18	[38], [40], [37]
Resorcinol	Phenolic acid	*	*	*	0.03	[40]
Vanillic Acid	Phenolic acid	*	8.19	1.77	0.43	[36], [41], [37]
Caffeic Acid/ Dactylifric Acid	Phenolic acid	*	3.56	2.15	0.03	[36], [40], [37]
Total Phenolics		158.0	48.0	37.0	22.11	[40], [42]
(+)–Catechin	Flavonoid	*	*	*	14.67	[40]
Trans–Ferulic acid		*	*	*	11.70	[40]
(-)–Epicatechin	Flavonoid	*	*	*	9.15	[40]
Rosmarinic acid		*	*	*	3.73	[40]
Total Polyphenols		295.0	150.0	22.0	20.0–24.58	[42], [43]
Quercetin	Flavonoid	*	1.05–2.48	7.19	1.22	[40], [36], [37]
Rutin	Flavonoid	*	*	36.41	0.85	[40], [37]
Isoquercetin	Flavonoid	*	*	*	0.41	[40]
Apigenin	Flavonoid	*	0.3–0.8	*	0.26	[40]
Luteolin	Flavonoid	*	1.93	*	0.04	[36]
Anthocyanins (Petunidine)	Flavonoid	*	31.0	2.0	1.0	[42]
Hesperidin	Flavonoid	*	3.5–4.72	*	*	[36]
Total flavonoids (mg QE/100g)		260.0–330	92.0–290	8.0–240	2.79–210	[40], [42], [3]

Description: * Not found in various literatures
Dates of the khalal phase using seed planting techniques in Thailand Gardens [36].

The literature does not yet provide a clear identification of the main bioactive ingredients in the Kimri stage. On the other hand, anthocyanins (petunidin), gallic acid, and ferulic acid are what define the Khalal stage. Gallic acid and protocatechuic acid predominate at the Rutab stage, though the data are still lacking. Major bioactive compounds are least abundant during the Tamar stage [44]. According to Table 1, the total phenolic content in the Kimri stage for date fruit pulp is roughly seven times higher than that in the Tamar stage when expressed on a fresh weight basis (FW), and the total polyphenol content is almost twelve times higher in the Kimri stage than in the Tamar stage. As ripening progresses from the early to the late stages, total flavonoid levels gradually decrease. In a similar vein, the tannin content drops dramatically, demonstrating a roughly 65% decrease from the Kimri to the Khalal stage.

Date acid is a distinctive phenolic compound that is only present in dates (*Phoenix dactylifera*). It is also referred to as dattelic acid or 5–O–caffeoylshikimic acid. Caffeic acid and shikimic acid conjugate to form this ester [45]. The enzymatic browning process that naturally occurs in dates uses date acid and its isomers as substrates. This substance has also been found in the date palm's roots and leaves in addition to its fruit [46]. As a component of date acid, caffeine has been shown to have significant biological activity, especially in preventing atherosclerosis by preventing low–density lipoprotein (LDL) from oxidising [47].

The shikimic acid pathway plays an important role in the biosynthesis of plant secondary metabolites, including flavonoids [48]. These phenolic and flavonoid compounds are widely distributed in plant organs and contribute to antioxidant activity by neutralizing free radicals and protecting biological systems from oxidative stress [48]. These compounds are widely distributed in plant organs such as roots, leaves, flowers, nectar, pollen, and seeds and are derived from phenolic substances [49]. Flavonoids share a basic C6–C3–C6 skeleton consisting of two aromatic rings linked by a three–carbon bridge, which may form a heterocyclic ring [50]. The hydroxyl groups present in most flavonoids can bind with sugars, increasing their water solubility [51].

These structures' capacity to scavenge free radicals is facilitated by the presence of numerous phenolic hydroxyl groups and conjugated double bonds, which alternate between single and double bonds. Through electron delocalisation, the benzene ring in this conjugated system also improves antioxidant qualities. One of the main flavonoid components in dates' fruit and seeds is catechin. Because catechin is highly polar, it is usually extracted using polar solvents, either separately or in combination, such as methanol (CH_3OH), ethanol (C_2H_6O), acetonitrile (CH_3CN), or acetone (C_3H_6O) [52]. According to reports, when compared to single solvents, solvent mixtures typically increase extraction efficiency.

3.3 *Date seeds*

Depending on the cultivar, date seeds—also known as pits, stones, or kernels—usually make up 10–15% of the fruit's weight [53]. These seeds are frequently used in animal feed and are frequently regarded as byproducts in a variety of industries. Date seeds exhibit promising antioxidant activity and cytocompatibility with normal human cell lines, according to new research that has highlighted their therapeutic potential [54] and is supported by findings from Jamil *et al.*, [55].

Date seeds have been shown in numerous studies to be non–toxic. Significant amounts of protein (5.1 g/100 g), fat (9.0 g/100 g), dietary fibre (73.1 g/100 g), phenolic compounds (3942 mg/100 g), and antioxidants are what define them nutritionally [56], [57]. Their moisture content normally falls between 7% and 12.5%, according to Hossain *et al.*, [58] and Shi *et al.*, [54]. Date seeds' phytochemical profile and antioxidant capacity differ significantly throughout their developmental stages, as shown in Table 2. The highest levels of total phenolics (27.38 mg/g DW), total tannins (17.7 mg/g DW), total flavonoids (12.83 mg/g DW), reducing power (153.03 mg/g DW), and overall antioxidant capacity (22.80 mg/g DW) were found at the Khalal stage, which occurred about three months after pollination. The Kimri stage, which occurred two months after pollination, came next, indicating that mid–development is when biosynthesis and the buildup of bioactive compounds peak [59]. According to these results, the best time of year to harvest date seeds with the highest antioxidant potential is during the Khalal stage. It is commonly known that phytochemicals like tannins, flavonoids, and phenolics are strong antioxidants. As secondary metabolites, they have important intracellular functions in plants and offer several health advantages to people, including reducing the risk of chronic illnesses like diabetes, cancer, and heart disease [57]. The valorization of underutilized by–products can contribute to the development of safe, natural, and multifunctional bioactive compounds, which have strong potential for application as functional materials in the food and pharmaceutical industries [60].

3.4 *Research gaps and systematic review in the utilization of date pulp and seeds as food ingredients*

The use of date pulp extracts as functional food ingredients has been the subject of an increasing amount of research. The use of extracts from "Ourrous" and "Ouksaba" cultivars obtained via Deep Eutectic Solvent (DES) extraction [61], the enrichment of camel milk powder with date–derived compounds [62], [63], the creation of date seed coffee substitutes [64], and the fortification of yoghurt beverages with tamar–stage extracts [65], [66], are a few examples. Table 3 presents a summary of these studies.

All of these studies highlight the great potential of date pulp and seeds, especially when they are at the tamar stage, to improve the nutritional, functional, and sensory qualities of food products [67]. To accomplish these results, a variety of extraction and processing methods have been effectively used, such as Soxhlet, supercritical CO_2, spray drying, and DES–based approaches. However, there is still a significant lack of information in the literature regarding the value–adding of date pulp and seeds at earlier developmental stages, like the kimri phase (about two months after pollination), which may also have substantial bioactive potential [68].

Table 2: Total phenolic content, tannin content, flavonoid content, reducing power, and total antioxidant capacity of date seeds at different developmental stages.

Developmental Stage (Months After Pollination)	Total Phenolic Content (mg/g DW)	Total Tannin Content (mg/g DW)	Total Flavonoid Content (mg/g DW)	Reducing Power (mg/g DW)	Total Antioxidant Capacity (mg/g DW)
1 Month (Hababouk)	15,9	10,2	5,3	114,55	15,02
2 Months (Kimri)	22,8	14,1	6,8	125,10	18,12
3 Months (Khalal)	27,38	17,7	12,83	153,03	22,8
4 Months (Tamar)	19,2	10,5	4,1	120,20	16,3

DW: Dry Weight; Source: [13].

This phase is characterized by a rising accumulation of bioactive compounds, yet it remains underexplored in food formulation applications. Further investigation into the kimri stage could reveal untapped potential for developing natural antioxidants, flavoring agents, or functional ingredients with distinctive physicochemical profiles [69]. Given the consistently higher polyphenol and antioxidant levels reported for the Kimri stage, this developmental phase offers strong potential for functional food applications. As such, marketing products derived from Kimri fruits as functional ingredients may enhance their perceived and actual health benefits.

A summary of studies looking into the use of date fruit and seed extracts in food formulations is provided in Table 3. Methodological diversity and possible application pathways are illustrated by highlighting differences in the kinds of raw materials used, the range of food applications targeted, the extraction and processing techniques used, and the resulting functional properties. In terms of raw materials, only one study used tamar–stage date seeds [64], while the majority used tamar–stage date fruit extracts [61], [62], [63], and [65]. This difference highlights a greater focus on fruit–derived compounds in research, with comparatively little investigation into seed–based applications, even though seeds are known to have bioactive potential.

In terms of uses, the research shows that various food systems that date extracts can be added to. Fruit extracts were used in the development of functional ingredients using green solvents [61]–[63] and yoghurt fortification [65]. In contrast, a different beverage application with potential consumer appeal was demonstrated by the processing of seed–derived material into caffeine–free date seed coffee powder [64]. As a result, seed applications have concentrated more on coffee substitutes, reflecting different product development trajectories, whereas fruit extracts have primarily been used as functional additives in dairy–based formulations. Additionally, the methods used in different studies differ significantly. The recovery of fruit extracts rich in bioactive compounds for yoghurt fortification was made possible by the combination of supercritical CO_2 techniques and conventional Soxhlet extraction [65]. Fruit extracts were more easily microencapsulated in camel milk powder through spray drying with MD acting as a carrier agent [62], [63], improving product stability.

Deep eutectic solvents [61] offer an inventive and environmentally friendly method that significantly improves phenolic recovery in contrast to traditional solvent extraction, highlighting their potential as green extraction media. Roasting and FTIR spectroscopy were used in the seed–based application [64], demonstrating a non–extraction–based strategy that aims to achieve value through product transformation as opposed to compound isolation. The flexibility of date–based resources to both established and new technologies is reflected in these methodological variations. According to the results, every study showed that the finished products had better functional or nutritional qualities. Without sacrificing sensory acceptability, yoghurt enhanced with tamar–stage fruit extract demonstrated increased phenolic content, antioxidant activity, viscosity, and colour stability [65]. Amorphous spherical morphology, low moisture content, good solubility, and improved thermal stability were among the positive physical attributes of camel milk powders enhanced with date extract [62], [63].

The effectiveness of green solvents in bioactive recovery was confirmed by the high phenolic yields and potent antioxidant activity obtained from extraction using DES [61]. In the meantime, it was established that roasted date seed coffee powder is caffeine–free, making it a viable functional substitute for regular coffee [64]. Altogether, the findings highlight two different ways of use: fruit extracts primarily improve the nutritional and functional qualities of well–known food products, while formulations made from seeds create new opportunities for the creation of caffeine–free drinks. All things considered, the comparative analysis shows that studies on date fruit and seed extracts cover a wide range of culinary uses, from beverage innovation to dairy fortification. Dates' versatility as functional food ingredients is highlighted by variations in material type, processing methods, and results. To maximise the nutritional, functional, and commercial potential of date–based products, future research should consider combining fruit and seed applications, methodically comparing extraction techniques, and evaluating consumer acceptance [70].

Table 3: Comparative summary of research on the utilization of date fruit and seed extracts as functional food ingredients.

Ripening phase	Application	Technique	Findings	References
Tamar–stage date fruit extract	Yogurt beverage fortification	Soxhlet extraction with n–hexane conducted at 70 °C for 10–12 h; Supercritical CO_2 extraction performed at 52.5 °C, 27.5 MPa, with a flow rate of 5 mL/min	Yoghurt fortification resulted in a decrease in lightness (L*) and yellowness (b*), while increasing total phenolic content, DPPH radical scavenging activity, viscosity, and redness (a). During refrigeration at 4 °C, the extract enhanced yoghurt quality without sacrificing its sensory acceptability	[65]
Tamar–stage date fruit extract	Fortification of camel milk powder	Spray drying at 160 °C, flow rate 7.0 mL/min, 3.1 wt/v% MD, outlet temp. 100 °C	At an inlet temperature of 160 °C, a feed flow rate of 7.0 mL/min, a maltodextrin concentration of 3.1 wt/v%, and an outlet temperature of 100 °C, spray drying was carried out.	[62], [63]
Tamar–stage 'Ourrous' and 'Ouksaba' date fruit extract (Algeria)	Potential food formulation using Deep Eutectic Solvent (DES)	Deep eutectic solvents–DES (lactic acid:sucrose, 3:1) prepared by stirring at 50 °C for 30–120 min; extraction of tamar–stage fruit using 100–200 mg/15 mL for 33 min	Strong DPPH activity and a high phenolic yield were attained. For functional bioactive recovery, double DES extraction worked well.	[61]
Tamar–stage date seeds	Date seed coffee powder	Seeds washed, dried, roasted at 125 °C for 30 min	FTIR spectroscopy verified that there was no caffeine present (no 1600–1800 cm^{-1} peaks), indicating that it would be a suitable substitute for coffee	[64]

3.5 *Encapsulation techniques of date pulp and seed extracts for food applications*

A useful tactic to increase the stability, bioavailability, and functional effectiveness of bioactive compounds found in date pulp and seeds in food systems is their encapsulation. A conceptual framework summarises existing encapsulation techniques, as illustrated in Figure 5, and Table 4 compiles data on wall materials, techniques, particle size properties, and possible uses. Mature dates (tamer stage) are used as the raw material in the majority of studies, mainly to produce functional ingredients like date sugar that are then added to food matrices like camel milk powder [63], [71].

Encapsulation had two primary functions in all five of the reviewed studies: (i) adding date–derived sugars or bioactives to food systems with enhanced functionality and process tolerance, and (ii) controlling release during storage and consumption. Encapsulation is designed to protect bioactives from degradation, as well as assist with controlled release during digestion or storage. Three entries focused on phenolic–rich date seed extracts with the goals of protection, controlled release, and bakery applications, while two entries concentrated on ingredients derived from tamr for dairy and sugar powders. This portfolio as a whole reflects a dual goal: enabling techno–functional improvements like flowability, solubility, and anti–staling properties while simultaneously stabilising heat–sensitive components during drying and subsequent processing [72].

Simple matrices based on carbohydrates and intricate multilayer systems are examples of coating materials. Because of its low viscosity, strong film–forming ability, and oxygen barrier qualities, maltodextrin (MD) is still the most commonly used encapsulating agent in spray drying. It is especially well–suited for dairy fortification, where neutral flavour and quick solubility are required [77], [78]. Gum arabic (GA) and MD work well together in binary systems because of their complementary properties. While MD facilitates the handling of solids, GA enhances surface activity and emulsification, which enhances the encapsulation efficiency of sugars and minor volatiles following supercritically assisted extraction. A core–shell–shell structure created especially for phenolic stabilisation is provided by more intricate tri–layer designs. These designs consist of medium–chain triglyceride (MCT) oil as the outer lipid layer, manna of Hedysarum gum or mangosteen gum as the intermediate shell, and MD as the inner glassy matrix [79].

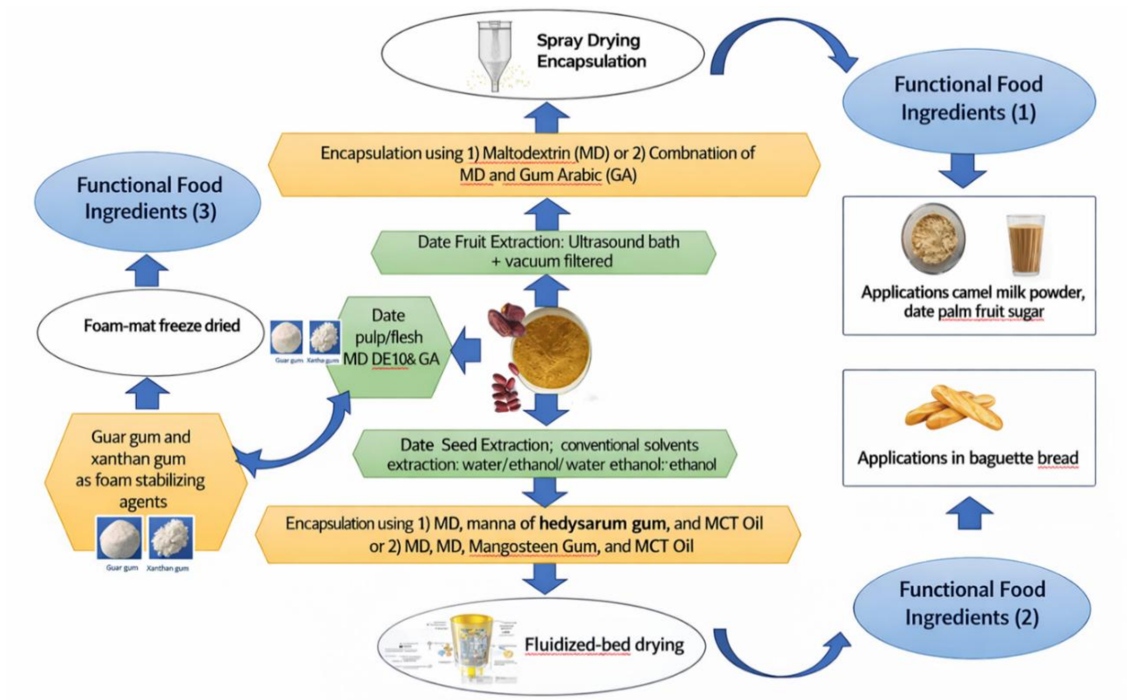

Figure 5: Framework for encapsulation techniques of date fruit and seeds for food applications.

Table 4: Overview of encapsulation techniques applied to date fruit and seed extracts and their functional utilization.

Encapsulation	Coating Material	Encapsulation Technique	Particle Size and Utilization	Reference
Application of date fruit extract (Tamr phase) in camel milk powder	Maltodextrin (MD)	Spray drying was performed at an inlet temperature of 160 °C with a feed rate of 7.0 mL/min, using 3.1 wt/v% maltodextrin (MD), resulting in an outlet temperature of 100 °C.	Spherical microparticles (1.2–27.7 µm; mean size: 9.1 ± 7.8 µm) were obtained, which were readily assimilated and contributed to enhanced thermal stability and nutritional quality of camel milk.	[73]
Date fruit (Tamr phase) processed into sugar	MD/Gum Arabic (GA) (1:1)	Supercritical-assisted aqueous extraction followed by spray drying (170 °C, 3 mL/min feed, 44% carrier concentration)	Average capsule size 11.3 µm (range 6–18 µm); powder particle size 6–24 µm; good yield (38.62%), low moisture (3.5%), high solubility (91.3%); density: 1.81 g/cm³	[71]
Phenolic compounds of date seed (*Phoenix dactylifera* L.)	MD (1st layer), *Manna of hedysarum* gum (MHG) (2nd), and MCT oil (3rd)	Extraction with water, ethanol,, as well as water–ethanol. The extracts were coated using maltodextrin (first layer), A MHG (second layer), and MCT oil (third layer) by a fluidized- bed dryer at 45 °C.	Powder sieved through 710 µm mesh; spherical and smooth particles; phenolic release peaked (64%) at 24 h; protected against heat (180 °C), light, and oxygen.	[74]
Effect of microencapsulated date seed extract on baguette bread quality	MD (1st), Mangosteen gum (2nd), MCT oil (3rd)	Extract, use a two-component solvent of water 25: ethanol 75. Microcoating of extracts using coating materials including fluidized-bed microcoating at 45 °C.	Bread with 1% nanocapsules (40% extract) had the lowest staling over 72 h and best sensory traits; highest phenolic content (231.12 mg GAE/µL) in 3% capsules with 50% extract.	[75]

Table 4: (Continued)

Encapsulation	Coating Material	Encapsulation Technique	Particle Size and Utilization	Reference
Date powder of Naghal cultivar 3 levels of ripeness (khalal–rutab–tamr)	MD DE10, or GA	Extraction of date pulp using MD and GA, then foam–mat freeze–dried with guar gum and xanthan gum as foam stabilizing agents.	Date powder produced with gum arabic (GA) exhibited lower moisture content (7.1–9.7%), particle density (1.5–1.6 g/cm³), and smaller particle size (47 ± 20 µm) compared to maltodextrin (MD)–based powder. Formulations containing 50% carrier demonstrated superior flowability relative to those with 40%. This makes the powder suitable as a food ingredient with reduced stickiness, attributed to the high glucose and fructose content in dates.	[76]

This multilayer structure strengthens mechanical integrity, increases moisture resistance, and permits controlled oxygen and light release. In foam–mat freeze–drying systems, GA has outperformed MD in producing powders with lower moisture content, density, and particle size because of its superior film formation at bubble interfaces—favorable properties for producing free–flowing sweet powders. Single–wall MD is usually sufficient for sugar–rich dairy applications, but hybrid carbohydrate–gum–lipid architectures are required for phenolic–rich seed extracts to achieve both protection and sustained release [78]. The functional results are heavily influenced by the carrier system and encapsulation technique selection. While foam–mat freeze–drying is useful for sugar–rich formulations that are prone to stickiness, fluidized–bed coating is appropriate for situations requiring a low thermal load, and spray drying is still the mainstay for producing soluble powders at scale. While micro–scale particle sizes (~6–30 µm) improve dispersibility in beverages and uniform incorporation into bakery systems, flowability and shelf–life stability in sugar–dense powders depend on moisture and density control. Solubility, flowability, oxidative stability, and anti–staling performance are ultimately determined by the carrier type (GA vs. MD), concentration (usually 40–50%), and presence of an outer lipid barrier (MCT) [80], [81].

3.5.1 Spray drying encapsulation

Spray drying is the most extensively utilized encapsulation process in food applications, primarily due to its industrial scalability, cost–effectiveness, and capacity to yield powders with desirable functional and structural characteristics [82]. The process generally proceeds through three sequential phases: atomization of the feed liquid, thermal drying of atomized droplets into solid particulates, and recovery of the dried product (Figures 5 and 6) [63]. The resulting particle size, determined by droplet size, can be precisely modulated through adjustments in operational variables, including feed rate, solute concentration, inlet and outlet temperatures, airflow conditions, and the type of atomization system employed. [83]. In this review, attention is given to wall materials commonly employed for encapsulating date fruit extracts, particularly MD and combinations of MD with GA. MD, a hydrolyzed starch derivative, is widely used as a wall or protective material in the microencapsulation of food ingredients [84].

3.5.1.1 Encapsulation using maltodextrin

Maltodextrin (DE 10–17) is frequently used as a single wall material because of its low hygroscopicity, high solubility, and neutral taste [85]. Microcapsules obtained using maltodextrin (MD) generally exhibit a spherical and amorphous morphology with a wide particle size distribution. In a study by Ricci *et al.*, (2022), MD achieved a higher polyphenol encapsulation efficiency (77%) than gum arabic (68%) in red grape pomace extract.

In the case of mature date fruit extract encapsulated into camel milk powder (Figure 6), ultrasonic–assisted extraction was followed by spray drying with varying MD concentrations [63]. A 30% MD concentration resulted in incomplete encapsulation and particle agglomeration due to surface stickiness. Increasing the concentration to 40% produced smoother, spherical particles (6–18 µm) with minimal agglomeration, while 50% MD generated larger particles (6–24 µm) due to higher feed viscosity, causing slight surface wrinkling but maintaining structural integrity. These results are consistent with previous studies showing that spray–drying parameters influence particle morphology, size, and solubility of milk powders [63].

Figure 6: Process representation of encapsulation date sugar camel milk powder production using spray–drying technique.

The optimized formulation obtained using Box–Behnken Design yielded up to 812 mg glucose equivalents/g date powder, along with fructose and sucrose, indicating potential as a nutritious alternative to refined sugar. The resulting microcapsules also showed favorable functional properties, including good solubility, cohesive powder behavior, desirable color, low moisture content, and predominantly amorphous spherical particles with a broad size distribution [86]. The resulting powder exhibits a predominantly amorphous matrix with the presence of localized crystalline domains. Such partial crystallinity is common in spray–dried and encapsulated materials, where rapid solvent evaporation promotes amorphous formation while residual ordering may occur due to specific interactions between carrier agents and bioactive compounds. Stating this explicitly provides a more accurate description of the powder's microstructure and aligns the interpretation of the physicochemical data with established morphological behavior in encapsulated systems [87]. The microcapsule powder predominantly exhibited an amorphous structure with small crystalline domains, consistent with previous observations reported by AlYammahi *et al.*, [63].

Analytical assessments using TGA, DSC, and chemical profiling further validated that date sugar–fortified camel milk powder (DCMP) possessed superior thermal resilience and improved nutritional attributes. The spray–dried DCMP thus represents a promising candidate for broad applications within the food and beverage sector. A key strength of this investigation lies in its originality, as it is the first to report on the development of camel milk powder enriched with date sugar. This adds value to the underutilized nutritional potential of both camel milk and date fruit by–products. The reported overall yield of 55 wt/wt.% is higher compared to similar studies on spray–dried food products, suggesting better process efficiency and industrial feasibility. The morphological traits (particle size 1.2–27.7 µm, spherical shape, amorphous nature) are consistent with desirable powder properties, ensuring better flowability, solubility, and packaging suitability [63].

It should be noted that while the study demonstrated improved physical stability with higher MD concentrations, optimization of carrier–to–core ratio should also consider cost implications for large–scale production. Yield, while moderate (55%), still falls below the industrial benchmarks of high spray–drying recovery (>70%), which may pose challenges for large–scale commercialization. Additional strategies to further improve yield should be discussed. The carrier agent concentration was very low (3.1 wt/v% MD). While this demonstrates a minimal additive approach, it also raises questions regarding long–term stability, as higher carrier concentrations are typically required to prevent stickiness, caking, and degradation of encapsulated sugars during storage.

The nutritional analysis, while reporting improvements (fiber, cholesterol, fatty acid profile), lacks evaluation of bioactive retention (e.g., phenolics, antioxidants, vitamins) after spray drying, which is critical for supporting functional food claims. While SEM and XRD confirm morphological stability, the claim of "good crystallinity" versus "amorphous structure" appears contradictory and should be clarified, since excessive crystallinity in sugar–containing powders may accelerate moisture uptake and reduce stability.

3.5.1.2 Encapsulation with a combination of maltodextrin and gum arabic

The utilization of maltodextrin (MD) as an encapsulating material provides distinct advantages, including low cost, absence of undesirable sensory attributes, maintenance of low viscosity at high solid levels, and reliable oxidative stability [88]. Nevertheless, its poor emulsifying capacity represents a major limitation, thereby necessitating its combination with surface–active biopolymers to optimize encapsulation efficiency.[89]. Mulcahy *et al.*, [90] observed that the hygroscopicity of maltodextrin (MD) is influenced by its dextrose equivalent (DE), with low–DE MD exhibiting minimal moisture absorption and high–DE MD showing increased hygroscopicity. Furthermore, MD alone tends to generate weak capsule structures and displays poor emulsifying properties, thereby requiring supplementation with encapsulants like gum arabic, which offers enhanced emulsification performance.

Najafi *et al.*, [91] demonstrated that encapsulants composed of polysaccharides (MD and GA) show higher oil retention capacity compared to protein–based encapsulants, thereby yielding better encapsulation efficiency and higher recovery. Polysaccharide–based materials, such as maltodextrin (MD) and gum arabic (GA), are widely utilized as carrier agents in food formulations owing to their cost–effectiveness, high solubility, oxidative resistance, thermal robustness, and excellent film–forming properties [92]. The flavor neutral nature and high solubility of MD–GA systems also makes MD–GA formulations a viable option in dairy and beverage formulations. In binary systems, MD offers a linear polymer backbone that supports coherent film formation, while GA provides a branched architecture that significantly improves emulsification efficiency and oxidative stability [93]. The functional synergy of these polymers is further reinforced through hydrogen bonding between hydroxyl groups within the wall materials and the sugars present in date extracts, thereby enhancing encapsulation integrity and ensuring greater physicochemical stability of the encapsulated bioactives applied supercritical CO_2–assisted extraction followed by spray drying using a 1:1 ratio of MD (DE 16.5-19.5) and GA (Figure 7) [71].

The powders produced under optimized spray–drying conditions were characterized by high solubility, low moisture levels, and enhanced sweetness in fortified camel milk powder, attributable to elevated glucose, fructose, and sucrose contents [82]. Fourier Transform Infrared (FTIR) spectroscopy confirmed the absence of chemical interactions between core and wall constituents, with O–H stretching band shifts pointing to hydrogen bond formation. Encapsulation with the MD–GA matrix yielded favorable physicochemical properties, including improvements in bulk density, solubility, flowability, tapped and particle densities, and color, along with reduced moisture content, thereby enhancing product stability, shelf life, and logistical handling. Importantly, the MD–GA system functioned as a highly effective carrier for soluble date sugar, producing powders with unique structural and functional attributes tailored for food applications [71].

A major contribution of this work is the rigorous application of the Box–Behnken Design (BBD) coupled with Response Surface Methodology (RSM), which facilitated parameter optimization with strong statistical validation of the interactive effects among carrier concentration, feed flow rate, and inlet temperature [94]. The use of MD and GA as a binary carrier system represent a relevant and innovative approach, since both agents are widely applied in food processing, but their combined optimization has rarely been reported, particularly for date sugar [95].

The morphology of date microcapsule powders produced with varying carrier concentrations, changes in carrier ratios, notably affected particle structure. SEM images indicate that all microcapsules were spherical but varied in size. At 30% carrier loading, the particles appeared continuous or fused, suggesting that this level of carrier was insufficient to fully encapsulate the sticky sugar components. A notable limitation of this study is the relatively low yield (38.62%), which may be considered less economical for industrial applications, as many food spray–drying studies typically report yields above >50-60% [96]. Another limitation lies in the absence of data concerning the retention of bioactive compounds (e.g., phenolics, antioxidants) or specific nutritional attributes after spray drying. Given that one of the primary purposes of microencapsulation is to preserve bioactives, this omission may weaken the functional claims of the product.

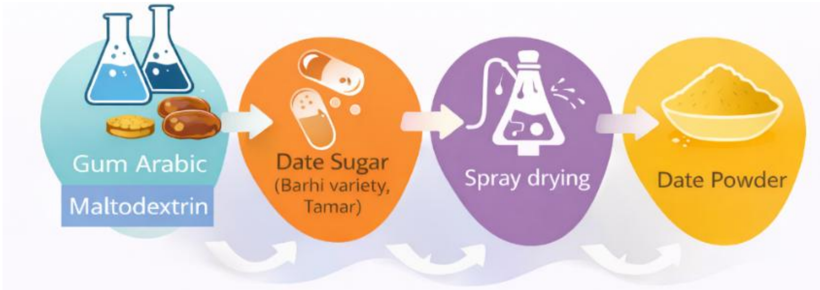

Figure 7: The encapsulation process of sugar extraction from dates with Gum Arab and Maltodextrin coatings using the spray drying technique.

Further studies should focus on enhancing the production yield to ensure industrial feasibility, possibly through alternative or synergistic carrier systems (e.g., proteins, inulin, or modified starches) that may improve both encapsulation efficiency and cost-effectiveness. Future work should incorporate systematic evaluations of bioactive retention and nutritional stability during both processing and storage to strengthen the evidence supporting the functional potential of date sugar powder. Moreover, long-term stability studies and pilot-scale validations are required to assess the reproducibility and scalability of the optimized spray-drying process under industrially relevant conditions. Importantly, integrating encapsulated date sugar into real-world food formulations, such as beverages, bakery items, or other consumer products, would provide critical insights into its technological functionality, market applicability, and overall consumer acceptance [27].

2.5.2 Advanced encapsulation via fluidized bed coating technology

Fluidized bed coating is recognized as a sophisticated encapsulation technique capable of producing multilayered structures that incorporate hydrophilic, structural, and hydrophobic layers. The method relies on passing heated air through the material bed to achieve fluidization, thereby facilitating uniform layer deposition. The efficiency of coating and the resulting particle morphology are strongly influenced by process variables such as inlet air temperature, airflow velocity, and bed depth [97].

The principle of microencapsulation using the fluidized–bed coating method involves suspending the core particles (phenolic extract from date seeds) in a fluidized state by an upward airflow, followed by spraying wall materials as fine droplets that adhere to the particle surface and dry to form microcapsules. The release mechanism of the active compounds is controlled rather than forced, meaning that the release occurs either through diffusion across the coating membrane or via the degradation of the encapsulating layer [74].

The stepwise mechanism begins with the introduction of the core particles (date seed phenol extract), which are fluidized by an upward stream of air. Wall materials such as MD, mangosteen gum, and MCT oil are then atomized through a nozzle into fine droplets. These droplets adhere to the particle surfaces during the fluidization cycle. Rapid drying by hot air subsequently solidifies the coating layer, resulting in stable microcapsules [98].

The encapsulated material can be applied across multiple food systems, with bread formulations serving as a representative example of its potential as a functional additive [75]. In the context of this review, the extraction of date seeds at the tamar stage (fully ripened) is particularly noteworthy, as it illustrates the implementation of three distinct wall material combinations designed to enhance encapsulation efficiency and stability. These include a combination of maltodextrin (MD), manna of hedysarum gum (MHG), and medium–chain triglyceride (MCT) oil, and a combination of maltodextrin (MD), mangosteen gum (MG), and medium–chain triglyceride (MCT) oil. The detailed discussion of these combinations is presented below.

3.5.2.1 Microencapsulation with maltodextrin (MD), manna of hedysarum gum (MHG), and medium–chain triglyceride (MCT) oil

The encapsulation manufacturing process (Figure 8) begins with the raw material of Estameran cultivar date seeds (Sayer date), which are cleaned and washed with distilled water. The date seeds are dried in a vacuum oven at 70 °C to a moisture content of 5%, and ground using an industrial grinding machine. The date powder is sieved through 710 microns (25 mesh) and stored in polyethylene packaging at 4 °C, then the phenolic components are extracted. The date seed extract is fluidized and encapsulated with maltodextrin, Manna of Hedysarum gum, and MCT oil (as a hydrophobic layer) [74].

The encapsulated phenolic compounds hold potential as functional food ingredients. Nevertheless, a critical limitation of this study lies in the drying conditions of date seeds, which were conducted at 70 °C. A lower drying temperature, preferably within the range of 50–60 °C, would be more appropriate to minimize the degradation of bioactive constituents [99]. Furthermore, the date seed powder was sieved only up to 25 mesh, whereas Muñoz–Tebar *et al.*, [100] reported that an optimum particle size for efficient phenolic extraction should be finer than 70 mesh (< 210 µm).

Strengths of the study, one of the major strengths of this study is the application of fluidized-bed drying, a relatively uncommon technique for the encapsulation of the date seed extract. The study demonstrates a comprehensive approach by systematically examining the influence of solvent type on phenolic content, antioxidant activity, microencapsulation performance, physicochemical characteristics, and the release dynamics of bioactive compounds.

Despite its valuable contributions, the study presents several limitations. The extraction approach employed in the study was limited to conventional solvent systems using ethanol and water, without incorporating more advanced methodologies such as ultrasound–assisted extraction (UAE), microwave–assisted extraction (MAE), or supercritical fluid extraction (SFE) [101]. These emerging technologies have been reported to enhance extraction yield, selectivity, and sustainability.

Furthermore, the study employed drying of date seeds at 70 °C, which may cause thermal degradation of heat–sensitive phenolic compounds. In addition, Muñoz–Tebar *et al.*, [100] highlighted that the particle size used in the study was 710 µm mesh, but previous authors have indicated that smaller particle sizes (i.e., <210 µm) should improve extraction efficiency. This study's main strength is the use of fluidized–bed drying, a microencapsulation method that is still largely underutilised for date seed extracts. By combining solvent selection, phenolic profiling, antioxidant capacity, encapsulation efficiency, physicochemical characterisation, and release kinetics of bioactive compounds, the study takes a comprehensive approach [102].

Future research should focus on the development and application of sustainable and environmentally benign extraction techniques, including enzymatic extraction, ultrasound–assisted processes, and natural deep eutectic solvents (NADES). Among these approaches, NADES have emerged as a promising class of carrier liquids formed through hydrogen bonding between hydrogen bond donors and acceptors, offering advantages such as high chemical purity, simple and cost–effective preparation, stability in the liquid state under ambient conditions, and strong potential as green solvents [103]. Additionally, studies addressing storage stability and simulated gastrointestinal digestion are warranted to provide deeper insights into the bioaccessibility and bioavailability of the encapsulated compounds [104]. Finally, incorporating microencapsulated date seed extracts into real food matrices, including beverages, edible oils, dairy systems, and bakery products, would allow for a more comprehensive evaluation of their functional properties, impact on product quality, and capacity to extend shelf life under practical conditions.

3.5.2.2 Encapsulation using maltodextrin, mangosteen gum, and MCT oil

This system replaces GA with mangosteen gum, a locally available material with antioxidant and emulsifying properties, combined with MCT oil to enhance moisture and oxidation resistance [100]. In baguette bread applications, 1% encapsulated extract improved loaf volume, texture, and phenolic retention after baking (Figure 9). This study introduces a novel approach by employing fluidized–bed microencapsulation of date seed extract using maltodextrin, mangosteen gum, and medium–chain triglyceride (MCT) oil as coating agents, which were subsequently incorporated into baguette bread formulations [75]. This approach effectively addresses both functional enhancement and quality improvement of bakery products. The findings highlight that microencapsulated date seed extract can significantly reduce bread staleness, enhance moisture retention, increase loaf volume, and improve porosity, softness, and chewability.

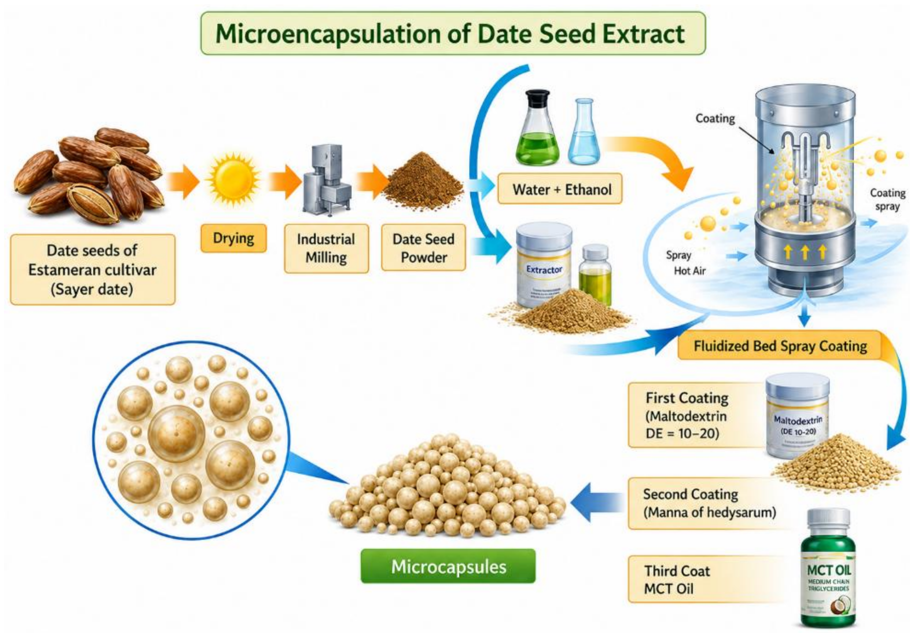

Figure 8: The encapsulation process of phenolic components of date palm seed extract using fluidized bed coating technique using maltodextrin, manna of hedysarum gum, and MCT oil [74] modified by the authors.

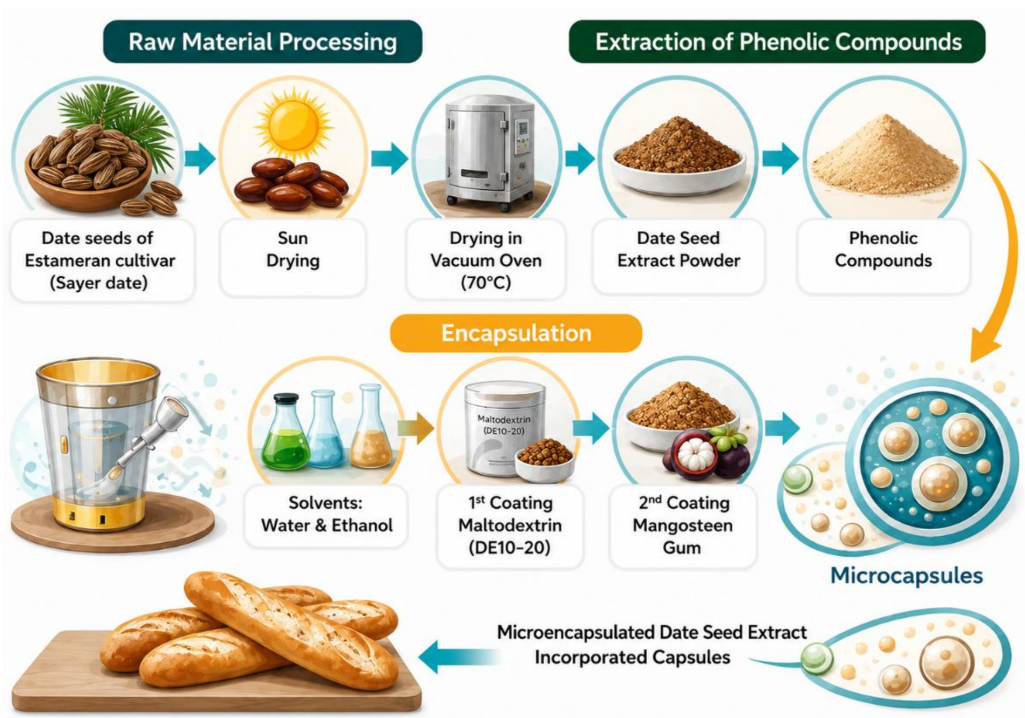

Figure 9: A fluidized bed coating technique was employed to microencapsulate date seed extract using maltodextrin, mangosteen gum, and MCT oil, and the resulting microcapsules were applied to baguette bread [75] modified by the authors.

Moreover, the encapsulation preserved phenolic compounds against environmental degradation, thereby improving their stability and potential bioavailability. The dual contribution—improvement of technological properties of bread and enrichment with bioactive compounds—underscores the study's relevance to both food science and functional food development.Despite its contributions, the study has several limitations. Firstly, the extraction of phenolic compounds from date seeds was limited to conventional methods, without the integration of advanced green extraction technologies such as ultrasound–assisted extraction (UAE) [105], microwave–assisted extraction (MAE) [106], or natural deep eutectic solvents (NADES) [107], which may offer improved phenolic yield and enhanced sustainability. Second, while the research investigated staleness and organoleptic properties, it lacked in–depth structural and mechanistic analysis of the dough and bread matrix (e.g., protein–polyphenol interactions, water mobility studies using NMR or DSC). Third, the study measured phenolic content but did not include antioxidant activity or bioavailability assays, which are essential to confirm the functional efficacy of the fortified bread. Finally, the sensory evaluation, although showing positive outcomes, was limited in scope and did not provide detailed consumer acceptance data across different demographic groups. The study title referred to microencapsulation (1–100 µm), but the text suggested nanoscale particles (10–500 nm) without providing post–encapsulation size data. The term 'nanocapsules' should be changed, or clarified, as the sizes reported happen to be in the microencapsulation range.

Future research should clarify particle size distribution and its correlation with release behavior in baked products [75]. The research makes a valuable contribution to the underexplored area of incorporating encapsulated date date seed extracts in bakery products. However, a critical concern is the balance between functional enrichment and sensory acceptance. While higher concentrations (e.g., 3% nanocapsules) provided greater phenolic content, they did not always correspond to the most desirable organoleptic qualities, indicating a potential trade-off between nutritional enhancement and consumer acceptance. Additionally, although encapsulation improved the stability of bioactive compounds, the release kinetics during baking and digestion remain insufficiently characterized. Without such information, the actual health–promoting potential of the enriched bread remains uncertain.

Future studies should: Adopt advanced and sustainable extraction methods (UAE, MAE, enzymatic–assisted extraction EAE, NADES) to improve yield, selectivity, and eco–friendliness of date seed phenolic recovery. Future investigations should focus on elucidating the structural and mechanistic aspects of fortified bread systems, particularly the interactions between gluten and polyphenols, gas retention dynamics, and water distribution within the bread matrix, employing advanced analytical techniques such as DSC, FTIR, rheology, and MRI/NMR [15], [53], [108]–[112]. In addition, a comprehensive evaluation of antioxidant activity, alongside the in vitro and in vivo assessment of phenolic bioaccessibility and bioavailability, including studies using simulated gastrointestinal digestion models, is recommended.

The extended storage stability studies were conducted to evaluate staling kinetics, oxidative stability, and phenolic retention over longer shelf–life conditions [113]. Expand sensory and consumer acceptance tests across diverse populations to validate the market feasibility of functional bread products enriched with date seed extracts. Explore application to other food systems (cakes, biscuits, dairy products, or plant–based foods) to widen the industrial utilization of encapsulated date seed bioactives.

A brief acknowledgment of consumer acceptance is warranted, as the successful application of encapsulated date fruit and seed extracts ultimately depends on sensory perception and market receptivity. Future studies should therefore incorporate structured consumer testing to evaluate flavor, aroma, texture, and overall acceptability across different demographic groups, as such insights are essential for aligning product development with consumer expectations and enhancing the commercial potential of functional food formulations incorporating these encapsulated ingredients.

3.5.3 Encapsulation with foam-mat freeze drying combined with MD or GA

The principle of foam–mat freeze drying (FMFD) comprises three sequential stages. First, foam formation is achieved by mixing the liquid material, such as date extract, with a foaming agent (e.g., proteins or natural surfactants) and carrier agents, most commonly maltodextrin (MD) or gum arabic

(GA) [114]. The mixture is aerated to generate a stable foam in which numerous air bubbles become entrapped. At this stage, MD and GA not only enhance foam stability and prevent collapse but also function as wall materials to encapsulate bioactive compounds [115]. Second, during freezing, the foam is rapidly frozen, resulting in the formation of ice crystals around the foam matrix. This step preserves the porous structure, stabilizes the encapsulating wall, and prevents structural collapse [116]. Third, freeze-drying (sublimation) is performed under reduced pressure and low temperature, whereby ice transitions directly from the solid to the vapor phase without passing through the liquid state. This process yields a porous, lightweight, and stable powder in which bioactive compounds are effectively entrapped within the maltodextrin (MD) or gum arabic (GA) matrix [117].

The encapsulation mechanism highlights the critical role of carrier agents. Maltodextrin, a water–soluble polysaccharide with low viscosity, forms a thin protective film that shields sensitive compounds from heat, oxygen, and moisture [118]. Gum arabic, a complex polysaccharide with excellent emulsifying capacity, stabilizes oil–water droplets, preserves volatile aroma compounds, and elevates the glass transition temperature, thereby reducing stickiness and enhancing storage stability [119]. During freezing, bioactive compounds such as date polyphenols are immobilized within the carrier matrix, while the porous structure formed during sublimation minimizes their exposure to oxygen and thermal degradation. The final microencapsulated product is a fine, porous powder that enables controlled release: when incorporated into food systems, MD or GA gradually dissolve, releasing the encapsulated compounds in a sustained and protected manner. Hence, FMFD with MD or GA is an effective encapsulation approach that produces powders with enhanced stability, solubility, and bioactivity of date–derived compounds.

Previous research has demonstrated the technical feasibility of FMFD for date–based systems. For example, Ruengdech and Siripatrawan [120] described FMFD as a process in which products are whipped with wall materials and foam stabilizers prior to freeze drying, yielding low–density powders (Figure 10). Seeranguruyar *et al.*, [76] applied guar gum and xanthan gum as foam stabilizers in date pulp (Naghal cultivar, three ripening stages) combined with MD or GA. The addition of stabilizers reduced drying time to 60–72 h compared with approximately five days in the absence of stabilizers. Moreover, powders produced with GA exhibited lower moisture content and smaller particle sizes than those obtained with MD. The study further demonstrated that carrier agents at 40% and 50% concentrations substantially improved the flowability and microstructural properties of the powders. Notably, GA at 50% yielded powders with superior flowability, reduced cohesiveness, and more desirable physical properties compared to MD or lower concentrations.

Comprehensive physicochemical assessments, including measurements of angle of repose, bulk and tapped densities, Carr Index, and Hausner ratio, offered critical insights into the flowability and handling characteristics of FMFD date powders, underscoring their significance for potential industrial–scale applications. To strengthen the practical potential of FMFD for date–based powders, several research directions are recommended. Nutritional and functional evaluation should be undertaken to assess the retention of bioactive compounds (e.g., phenolics, flavonoids, and antioxidants) as well as the glycemic impact of carrier–enriched powders [121].

Figure 10: Foam mat freeze drying (FMFD) processing at different ripening stages.

Comparative drying studies are necessary to benchmark FMFD against alternative drying methods, thereby identifying the most efficient and scalable approaches. Future application-oriented research should prioritize the integration of date powders into diverse food matrices, including bakery, confectionery, beverage, and dairy systems—with particular emphasis on their role as natural sugar alternatives [122].

Sensory and consumer acceptance studies are essential to evaluate flavor, aroma, and overall palatability, ensuring consumer acceptance in real–world food applications [123]. In addition, shelf–life and stability assessments are needed to determine hygroscopicity, caking tendency, and storage stability under different environmental conditions. Finally, optimization of carrier concentration and selection should be explored by testing alternative systems (e.g., resistant starch, inulin, or protein–based carriers) to reduce the proportion of carrier required while maintaining powder flowability and minimizing the dilution of bioactive compounds [124]. FMFD represents an innovative and promising approach to overcoming the stickiness and hygroscopicity challenges of date sugars while preserving the structural integrity of powders. However, the method is time– and energy–intensive, which may limit its industrial scalability. Future work should focus on optimizing process efficiency, carrier composition, and functional quality to balance technological performance with nutritional preservation. Such efforts will be essential for translating FMFD from laboratory–scale feasibility studies into commercially viable, nutritionally relevant, and consumer–acceptable date–based food ingredients.

3.6 *Implication for future research*

The bibliometric analysis offers a robust basis for delineating key avenues for future investigations on bioactive compounds extracted from date palm fruits and seeds. While studies on antioxidant activity and phenolic content are relatively well established, several emerging and underexplored areas present substantial opportunities to advance scientific knowledge and technological applications in this field.

1) Green and Sustainable Extraction Technologies

An important research gap lies in the limited exploration of green solvent–based extraction of bioactive compounds from tropical date palm (KL–1) at the kimri stage, particularly using Natural Deep Eutectic Solvents (NADES). Environmentally sustainable approaches—including ultrasound–assisted extraction, microwave–assisted extraction, supercritical CO_2 extraction, and NADES—have been seldom reported in the bibliometric literature, despite their potential as eco–friendly alternatives to conventional solvent–based techniques. Future investigations should prioritize the optimization of these methods to enhance extraction efficiency, compound purity, and overall environmental sustainability [70].

2) Valorization of Local and Tropical Cultivars

The near-complete absence of tropical date cultivars, such as KL–1, from the bibliometric network reveals a significant research gap. Comprehensive studies on the phytochemical composition, functional properties, and potential food applications of region–specific date varieties could foster the development of localized solutions and novel products. The bioactive profile of tropical KL–1 fruit and seeds at the kimri stage remains unreported and warrants detailed investigation [125].

3) Functional Evaluation and Bioaccessibility

Research on the development of kimri–stage KL–1 extracts as functional food ingredients and antioxidants is lacking. Keywords such as bioaccessibility, biocompatibility, and antioxidant stability indicate a growing trend towards functional validation. Future work should employ in vitro digestion models, animal studies, and clinical trials to bridge the gap between extraction-based studies and substantiated health claims [126]–[128].

4) Advanced Encapsulation and Delivery Systems

Techniques Keywords such as nanoemulsion, spray drying, and high–pressure homogenization suggest increased interest in improving the bioavailability and stability of date-derived bioactives. These methods should be explored further, particularly in combination with innovative wall materials and targeted delivery systems for functional foods or nutraceuticals. The encapsulation of kimri–stage date extracts to enhance the physicochemical stability of coconut skim milk, for instance, remains unexplored [129], [130].

5) Interdisciplinary Integration and Predictive Modeling

The increasing application of computational approaches, including response surface methodology (RSM), artificial neural networks (ANN), and COSMO–RS modeling, reflects a growing transition toward predictive.

These methods can accelerate optimization of the extraction and formulation process, reduce experimental costs, and enable the prediction of stability or activity under various environmental and processing conditions [73], [131], [132].

3.7 *Global estimates and industrial potential of kimri-stage date fruit and seed by-products*

At the global level, immature dates at the kimri stage are predominantly consumed fresh in limited quantities or utilized in niche industrial applications, particularly within the Middle East and North Africa. Compared with fully ripened tamar-stage fruits, kimri seeds are smaller in size and exhibit a lower degree of structural development. Due to their limited consumption and regional specificity, the volume of kimri seed waste is relatively low and remains undocumented. A preliminary estimate – assuming that 1–2% of global date production (9.66 million tonnes annually [133], [134]) is consumed at the kimri stage – suggests potential seed waste of approximately 50,000 – 100,000 tonnes per year, though this figure requires empirical validation.

Kimri fruits are rich in phenolics, tannins, and flavonoids, often at higher levels than in mature dates, making them promising raw materials for antioxidant extract, functional beverages, and fermented products [135]. They are occasionally processed into candied or snack forms. Kimri seeds, despite their smaller size and lower nutritional maturity, have demonstrated notable antioxidant potential, in some cases surpassing that of mature seeds [4]. Emerging applications include their use as sources of polyphenols in cosmetics and nutraceuticals, and as raw materials for bioplastics or adsorbents in environmental and material science applications. However, their hardness and processing difficulty remain significant challenges.

Overall, the fruit and seeds of kimri–stage dates represent an underutilized yet highly promising resource for industrial exploitation. Strategic research focused on their extraction, functional validation, and incorporation into food, pharmaceutical, and cosmetic products could unlock considerable commercial, sustainable, and health–promoting value.

4 Conclusions

The bioactive profile of date palm fruit at the kimri stage (green phase) remains insufficiently characterized, although this developmental stage has been reported to contain the highest concentrations of total phenolics, flavonoids, and polyphenols relative to mature fruits. In contrast, date seeds exhibit their peak bioactive content at the khalal stage, followed by the kimri stage. Bibliometric analysis has revealed key research gaps, notably the absence of studies on the extraction of bioactive compounds from tropical date palm (KL-1) at the kimri stage using green solvents—particularly Natural Deep Eutectic Solvents (NADES) coupled with ultrasound-assisted extraction—which has not yet been explored; 2) the bioactive composition of tropical date palm (KL-1) fruit and its seed valorization at the kimri stage remains unexplored; 3) the development of KL-1 kimri stage extracts as food ingredients an natural antioxidants has not been investigated; and 4) the encapsulation of kimri-stage date extracts to enhance physicochemical stability, for example in coconut skim milk, has not been studied. The review also highlights that most applications of date pulp and seeds valorization through encapsulation technologies as food ingredients and their integration into food matrices have primarily focused on the mature stage (tamer). Encapsulation technology provides several advantages, including protecting bioactive compounds, antioxidants, and nutrients during high-temperature processing, as well as enhancing their bioaccessibility, biocompatibility, and physicochemical stability. These insights highlight significant opportunities for advancing research on bioactive compounds from tropical date palm and their prospective utilization as functional ingredients within food systems.

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Author Contributions

A.Y.P.: conceptualization, investigation, methodology topic organization, writing an original draft; S.Y.: methodology, reviewing, editing, and supervision; N.E.S.: methodology, reviewing, and supervision; S.A.Y.: investigation, reviewing, and supervision. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

References

[1] H. M. T. Al-Safy and R. S. Ali, "Effect of the variety and processing method on the productivity and quality of date molasses," *IOP Conference Series: Earth and Environmental Science*, vol. 1262, no. 6, pp. 1–6, 2023, doi: 10.1088/1755-1315/1262/6/062057.

[2] U. Roobab, R. M. Aadil, S. S. Kurup, and S. Maqsood, "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," *Ultrasonics Sonochemistry*, vol. 114, 2025, Art. no. 107252, doi: 10.1016/j.ultsonch.2025.107252.

[3] Y. Bano, A. Rakha, M. I. Khan, and M. Asgher, "Chemical composition and antioxidant activity of date (*Phoenix dactylifera* L.) varieties at various maturity stages," *Food Science and Technology (Brazil)*, vol. 42, 2022, Art. no. e29022 doi: 10.1590/fst.29022.

[4] A. Othmani, M. Jemni, K. Kadri, S. Amel, F. Artés, and J. M. Al-Khayri, "Preharvest fruit drop of date palm (*Phoenix dactylifera* L.) Cv. Deglet Nour at kimri stage: Development, physico-chemical characterization, and functional properties," *International Journal of Fruit Science*, vol. 20, no. 3, pp. 414–432, 2020, doi: 10.1080/15538362.2019.1651241.

[5] M. Mohammed, H. El-Shafie, and M. Munir, "Development and validation of innovative machine learning models for predicting date palm Mite infestation on fruits," *Agronomy*, vol. 13, no. 2, 2023, Art. no. 494, doi: 10.3390/agronomy13020494.

[6] S. Ghnimi, S. Umer, A. Karim, and A. Kamal-Eldin, "Date fruit (*Phoenix dactylifera* L.): An underutilized food seeking industrial valorization," *NFS Journal*, vol. 6, pp. 1–10, 2017, doi: 10.1016/j.nfs.2016.12.001.

[7] M. Mohammed, A. Sallam, N. Alqahtani, and M. Munir, "The combined effects of precision-controlled temperature date fruit," *Foods*, vol. 10, no. 11, 2021, Art. no. 2636, doi: doi.org/10.3390/foods10112636.

[8] A. Ouamnina, A. Alahyane, I. Elateri, A. Boutasknit, and M. Abderrazik, "Relationship between phenolic compounds and antioxidant activity of some Moroccan date palm fruit varieties (*Phoenix dactylifera* L.): A two-year study," *Plants*, vol. 13, no. 8, pp. 1–20, 2024, doi: 10.3390/plants13081119.

[9] STATISTA, "Production of dates worldwide from 2010 to 2023 (in million metric tons)," statista.com. Accessed: Sep. 10, 2025. [Online]. Available:https://www.statista.com/statistics/960247/dates-production-worldwide/

[10] I. Zahid, M. H. Nazir, and M. A. Javed, "Extraction of bioactive components from date palm waste, various extraction processes and their applications: A review," *Biomass and Bioenergy*, vol. 190, 2024, Art. no. 107433, doi:10.1016/j.biombioe.2024.10743.

[11] P. Chanphai and H. A. Tajmir-Riahi, "Tea polyphenols bind serum albumins: A potential application for polyphenol delivery," *Food Hydrocolloids*, vol. 89, no. 4, pp. 461–467, 2019, doi: 10.1016/j.foodhyd.2018.11.008.

[12] M. M. Zadeh, P. Dehghan, and Z. Eslami, "Effect of date seed (*Phoenix dactylifera*) supplementation as functional food on cardiometabolic risk factors, metabolic endotoxaemia and mental health in patients with type 2 diabetes mellitus: A blinded randomised controlled trial protocol," *BMJ Open*, vol. 13, 2023, Art. no. e066013, doi: 10.1136/bmjopen-2022-066013.

[13] A. Bijami, F. Rezanejad, H. Oloumi, and H. Mozafari, "Minerals, antioxidant compounds and phenolic profile regarding date palm (*Phoenix dactylifera* L.) seed development," *Scientia Horticulturae*, vol. 262, no. 4, 2020, Art. no. 109017, doi: 10.1016/j.scienta.2019.109017.

[14] N. A. AlFaris et al., "Total phenolic content in ripe date fruits (*Phoenix dactylifera* L.): A systematic review and meta-analysis," *Saudi Journal of Biological Sciences*, vol. 28, no. 6, pp. 3566–3577, 2021, doi: 10.1016/j.sjbs.2021.03.033.

[15] M. Ranasinghe et al., "Valorizing date seeds in biscuits: A novel approach to incorporate bioactive components extracted from date seeds

using microwave-assisted extraction," *Resources, Environment and Sustainability*, vol. 15, 2024, Art. no. 100147, doi: 10.1016/j.resenv.2023.100147.

[16] O. Airouyuwa, H. Mostafa, A. Riaz, and S. Maqsood, "Utilization of natural deep eutectic solvents and ultrasound-assisted extraction as green extraction technique for the recovery of bioactive compounds from date palm (*Phoenix dactylifera* L.) seeds: An investigation into optimization of process parameters," *Ultrasonics Sonochemistry*, vol. 91, 2022, Art. no. 106233, doi: 10.1016/j.ultsonch.2022.106233.

[17] K. Ghafoor et al., "Innovative and green extraction techniques for the optimal recovery of phytochemicals from saudi date fruit flesh," *Processes*, vol. 10, no. 11, pp. 1–16, 2022, doi: 10.3390/pr10112224.

[18] L. E. Kurozawa, I. Terng, M. D. Hubinger, and K. J. Park, "Ascorbic acid degradation of papaya during drying: Effect of process conditions and glass transition phenomenon," *Journal of Food Engineering*, vol. 123, no. 4, pp. 157–164, 2014, doi: 10.1016/j.jfoodeng.2013.08.039.

[19] R. ElGamal, C. Song, A. M. Rayan, C. Liu, S. Al-Rejaie, and G. ElMasry, "Thermal degradation of bioactive compounds during drying process of horticultural and agronomic products: A comprehensive overview," *Agronomy*, vol. 13, no. 6, 2023, Art. no. 1580, doi: 10.3390/agronomy13061580.

[20] V. Eyarkai Nambi, R. K. Gupta, S. Kumar, and P. C. Sharma, "Degradation kinetics of bioactive components, antioxidant activity, colour and textural properties of selected vegetables during blanching," *Journal of Food Science and Technology*, vol. 53, no. 7, pp. 3073–3082, 2016, doi: 10.1007/s13197-016-2280-2.

[21] E. Demiray and Y. Tulek, "Color degradation kinetics of carrot (Daucus carota L.) slices during hot air drying," *Journal of Food Processing and Preservation*, vol. 39, no. 6, pp. 800–805, 2015, doi: 10.1111/jfpp.12290.

[22] S. Singhal, P. Rasane, S. Kaur, J. Singh, and N. Gupta, "Thermal degradation kinetics of bioactive compounds in button mushroom (Agaricus bisporus) during tray drying process," *Journal of Food Process Engineering*, vol. 43, 2020, Art. no. e13555, doi: 10.1111/jfpe.13555.

[23] A. Kaewchada and R. Chongcharoen, "Continuous encapsulation of vitamin E using polycaprolactone and tween 20 in a micro-channel," *Applied Science and Engineering Progress*, vol. 16, no. 1, 2023, Art. no. 5556, doi: 10.14416/j.asep.2022.01.001.

[24] A. Hai, K. Rambabu, A. S. Al Dhaheri, S. S. Kurup, and F. Banat, "Tapping into palm sap: Insights into extraction practices, quality profiles, fermentation chemistry, and preservation techniques," *Heliyon*, vol. 10, 2024, Art. no. e35611, doi: 10.1016/j.heliyon.2024.e35611.

[25] A. Dantas, D. P. Costa, X. Felipe, and P. Gou, "Innovations in spray drying technology for liquid food processing: Design, mechanisms, and potential for application," *Applied Food Research*, vol. 4, 2024, Art. no. 100382, doi: 10.1016/j.afres.2023.100382.

[26] P. Labuschagne, "Impact of wall material physicochemical characteristics on the stability of encapsulated phytochemicals: A review," *Food Research International*, vol. 107, pp. 227–247, 2018, doi: 10.1016/j.foodres.2018.02.026.

[27] C. I. Piñón-Balderrama, C. Leyva-Porras, Y. Terán-Figueroa, V. Espinosa-Solís, C. Álvarez-Salas, and M. Z. Saavedra-Leos, "Encapsulation of active ingredients in food industry by spray-drying and nano spray-drying technologies," *Processes*, vol. 8, no. 8, 2020, Art. no. 889, doi: 10.3390/PR8080889.

[28] P. Kaushik, K. Dowling, S. McKnight, C. J. Barrow, and B. Adhikari, "Microencapsulation of flaxseed oil in flaxseed protein and flaxseed gum complex coacervates," *Food Research International*, vol. 86, pp. 1–8, 2016, doi: 10.1016/j.foodres.2016.05.015.

[29] M. Nizar, S. Yana, Bahagia, Erdiwansyah, R. Mamat, and V. Viena, "Bibliometric analysis of global research on organic waste enzymes for plastic biodegradation: Trends, microbial roles, and process optimization," *Cleaner and Circular Bioeconomy*, vol. 12, 2025, Art. no. 100164, doi: 10.1016/j.clcb.2025.100164.

[30] Sunaryo, Suyitno, Z. Arifin, and M. Setiyo, "High yield oil from catalytic pyrolysis of polyethylene terephthalate using natural zeolite: A review," *Applied Science and Engineering Progress*, vol. 18, no. 3, 2025, Art. no. 7673, doi: 10.14416/j.asep.2025.01.001.

[31] B. O. Olorunfemi, N. I. Nwulu, O. A. Adebo, and K. A. Kavadias, "Advancements in machine visions for fruit sorting and grading: A bibliometric analysis, systematic review, and future research directions," *Journal of*

Agriculture and Food Research, vol. 16, 2024, Art. no. 101154, doi: 10.1016/j.jafr.2024.101154.

[32] M. Olaya and D. Salma, "Bibliometric mapping of research on artificial intelligence applied to fintech and financial," *International Journal of Innovative Research and Scientific Studies*, vol. 8, no. 8, pp. 296–312, 2025, doi: 10.53894/ijirss.v8i8.10590.

[33] M. N. Ajemba and E. C. Arene, "Research gaps for future research and their identification," *World Journal of Advanced Research and Reviews*, vol. 16, no. 1, pp. 575–579, 2022, doi: 10.30574/wjarr.2022.16.1.1062.

[34] N. M. S. Eid, B. Al-Awadi, D. Vauzour, M. J. Oruna-Concha, and J. P. E. Spencer, "Effect of cultivar type and ripening on the polyphenol content of date palm fruit," *Journal of Agricultural and Food Chemistry*, vol. 61, no. 10, pp. 2453–2460, 2013, doi: 10.1021/jf303951e.

[35] J. Hinkaew, Y. Sahasakul, N. Tangsuphoom, and U. Suttisansanee, "The effect of cultivar variation on total phenolic contents and antioxidant activities of date palm fruit (*Phoenix dactylifera* L.)," *Current Research in Nutrition and Food Science*, vol. 8, no. 1, pp. 155–163, 2020, doi: 10.12944/CRNFSJ.8.1.14.

[36] J. Hinkaew, A. Aursalung, Y. Sahasakul, N. Tangsuphoom, and U. Suttisansanee, "A comparison of the nutritional and biochemical quality of date palm fruits obtained using different planting techniques," *Molecules*, vol. 26, no. 8, 2021, Art. no. 2245, doi: 10.3390/molecules26082245.

[37] H. H. A. Khalaf, R. M. A. Al-Saadany, and Y. A. Nezam El-Din, A. M. M Salem, "Nutritional evaluation, antioxidant, anticancer and antimicrobial activities of egyptian amhat date palm fruit," in *5th International Conference on Biotechnology Applications in Agriculture (ICBAA)*, 2021, pp. 421–432. doi: 10.21608/assjm.2021.195008.

[38] M. Al-Hilal, Z. Moussa, and A. Anderson, "Nutritional composition and biochemical characteristics of five date palm fruit (*Phoenix dactylifera* L.) varieties at the Khalal stage grown in Kuwait," *Kuwait Journal Science*, vol. 50, no. 1A, pp. 1–11, 2023, doi: 10.48129/kjs.17169.

[39] M. Tassoult, D. E. Kati, M. Á. Fernández-Prior, A. Bermúdez-Oria, J. Fernandez-Bolanos, and G. Rodríguez-Gutiérrez, "Antioxidant capacity and phenolic and sugar profiles of date fruits extracts from six different algerian cultivars as influenced by ripening stages and extraction systems," *Foods*, vol. 10, no. 3, 2021, Art. no. 503, doi: 10.3390/foods10030503.

[40] I. Hamad et al., "Metabolic analysis of various date palm fruit (*Phoenix dactylifera* L.) cultivars from Saudi Arabia to assess their nutritional quality," *Molecules*, vol. 20, no. 8, pp. 13620–13641, 2015, doi: 10.3390/molecules200813620.

[41] I. Odeh, F. Al-Rimawi, J. Abbadi, L. Obeyat, M. Qabbajeh, and A. Hroub, "Effect of harvesting date and variety of date palm on antioxidant capacity, phenolic and flavonoid content of date palm (*Phoenix dactylifera*)," *Journal of Food and Nutrition Research*, vol. 2, no. 8, pp. 499–505, 2014, doi: 10.12691/jfnr-2-8-11.

[42] N. Eid et al., "The impact of date palm fruits and their component polyphenols, on gut microbial ecology, bacterial metabolites and colon cancer cell proliferation," *Journal of Nutritional Science*, vol. 3, no. 22, pp. 1–9, 2014, doi: 10.1017/jns.2014.16.

[43] B. Y. Sheikh et al., "Comparative study of neuropharmacological, analgesic properties and phenolic profile of Ajwah, Safawy and Sukkari cultivars of date palm (*Phoenix dactylifera*)," *Oriental Pharmacy and Experimental Medicine*, vol. 16, no. 3, pp. 175–183, 2016, doi: 10.1007/s13596-016-0239-5.

[44] L. Shi et al., "Ripening stage and phenolic composition characterization of fruit from different date (*Phoenix dactylifera* L.) cultivars in Australia," *Food Science and Nutrition*, vol. 13, 2025, Art. no. e70221, doi: 10.1002/fsn3.70221.

[45] M. Fukuoka, "Chemical and toxicological studies on Bracken fern, Pteridium aquilinum var. latiusculum: Isolation of 5-O-Caffeoylshikimic acid as an antithiamine factor," *Chemical Pharmaceutical Bulletin*, vol. 9, no. 43, pp. 3219–3224, 1982, doi: 10.1248/cpb.30.3219.

[46] A. Ziouti, C. El Modafar, A. Fleuriet, S. El Boustani, and J. J. Macheix, "Phenolic compounds in date palm cultivars sensitive and resistant to Fusarium oxysporum," *Biologia Plantarum*, vol. 38, no. 3, pp. 451–457, 1996, doi: 10.1007/BF02896679.

[47] S. Ahmed, R. A. Khan, and S. Jamil, "Anti

hyperlipidemic and hepatoprotective effects of native date fruit variety 'Aseel' (*Phoenix dactylifera*)," *Pakistan Journal of Pharmaceutical Sciences*, vol. 29, no. 6, pp. 1945–1950, 2016, doi: pubmed.ncbi.nlm.nih.gov/28375109/.

[48] G. R. Egarani, "The antioxidant compounds and antioxidant activity in various plant organs of kitolod (Isotoma longiflora)," *Journal of Biology & Biology Education*, vol. 12, no. 3, pp. 297–303, 2020, doi: 10.15294/biosaintifika.v12i3.23888.

[49] D. Tungmunnithum, A. Thongboonyou, A. Pholboon, and A. Yangsabai, "Flavonoids and other phenolic compounds from medicinal plants for pharmaceutical and medical aspects: An overview," *Medicines*, vol. 5, no. 3, 2018, Art. no. 93, doi: 10.3390/medicines5030093.

[50] W. Liu et al., "The flavonoid biosynthesis network in plants," *International Journal of Molecular Sciences*, vol. 22, no. 23, 2021, Art. no. 12824, doi: 10.3390/ijms222312824.

[51] P. Pinho and O. Ferreira, "Solubility of flavonoids in pure and mixed solvents," *Industrial & Engineering Chemistry Research*, vol. 51, no. 18, pp. 6586–6590, 2012, doi: 10.1021/ie300211e.

[52] Y. J. Tsai and B. H. Chen, "Preparation of catechin extracts and nanoemulsions from green tea leaf waste and their inhibition effect on prostate cancer cell PC-3," *International Journal of Nanomedicine*, vol. 11, no. 5, pp. 1907–1926, 2016, doi: 10.2147/IJN.S103759.

[53] M. A. Bouaziz, W. B. Amara, H. Attia, C. Blecker, and S. Besbes, "Effect of the addition of defatted date seeds on wheat dough performance and bread quality," *Journal of Texture Studies*, vol. 41, no. 4, pp. 511–531, 2010, doi: 10.1111/j.1745-4603.2010.00239.x.

[54] L. Shi et al., "Valorization of date fruit (*Phoenix dactylifera* L.) processing waste and by-products: A review," *Applied Sciences (Switzerland)*, vol. 13, no. 22, 2023, doi: 10.3390/app132212315.

[55] N. A. M. Jamil, J. R. Al-Obaidi, N. M. Saleh, and N. N. Jambari, "Comparative nutritional and toxicity analyses of beverages from date seed and barley powders as caffeine-free coffee alternatives," *International Food Research Journal*, vol. 29, no. 4, pp. 786–795, 2022, doi: 10.47836/ifrj.29.4.06.

[56] M. S. Baliga, B. R. V. Baliga, S. M. Kandathil, H. P. Bhat, and P. K. Vayalil, "A review of the chemistry and pharmacology of the date fruits (*Phoenix dactylifera* L.)," *Food Research International*, vol. 44, no. 7, pp. 1812–1822, 2011, doi: 10.1016/j.foodres.2010.07.004.

[57] M. A. Al-Farsi and C. Y. Lee, "Nutritional and functional properties of dates: A review," *Critical Reviews in Food Science and Nutrition*, vol. 48, no. 10, pp. 877–887, 2008, doi: 10.1080/10408390701724264.

[58] M. Z. Hossain, M. I. Waly, V. Singh, V. Sequeira, and M. S. Rahman, "Chemical composition of date-pits and its potential for developing value-added product - A review," *Polish Journal of Food and Nutrition Sciences*, vol. 64, no. 4, pp. 215–226, 2014, doi: 10.2478/pjfns-2013-0018.

[59] K. Karim, A. Karim, H. Hamza, A. Manar, C. Karmous, and T. Bettaieb, "Effect of pollination technique on agronomic and physicochemical characteristics of date palm fruits (*Phoenix dactylifera* L.) cv. 'Deglet Nour'," *Horticultural Science and Technology*, vol. 40, no. 2, pp. 121–133, 2022, doi: 10.7235/HORT.20220012.

[60] P. Muangrod et al., "Valorization of jellyfish (Rhopilema hispidum) by-products for bioactive peptides with antibacterial, enzyme inhibitory, and low cytotoxic activities," *Applied Science and Engineering Progress*, vol. 19, no. 1, pp. 1–14, 2026, doi: 10.14416/j.asep.2025.09.001.

[61] O. Djaoudene and H. Louaileche, "Optimization of a green ultrasound-assisted extraction of phenolics and in vitro antioxidant potential of date fruit (*Phoenix dactylifera* L.)," *Annals of the University Dunarea de Jos of Galati, Fascicle VI: Food Technology*, vol. 42, no. 1, pp. 109–122, 2018.

[62] J. AlYammahi, A. Hai, R. Krishnamoorthy, T. Arumugham, S. W. Hasan, and F. Banat, "Ultrasound-assisted extraction of highly nutritious date sugar from date palm (*Phoenix dactylifera*) fruit powder: Parametric optimization and kinetic modeling," *Ultrasonics Sonochemistry*, vol. 88, 2022, Art. no. 106107, doi: 10.1016/j.ultsonch.2022.106107.

[63] J. AlYammahi et al., "Production and characterization of camel milk powder enriched with date extract," *Lwt*, vol. 179, 2023, Art. no. 114636, doi: 10.1016/j.lwt.2023.114636.

[64] C. D. Venkatachalam and M. Sengottian, "Study on roasted date seed non caffeinated coffee powder as a promising alternative," *Asian*

Journal of Research in Social Sciences and Humanities, vol. 6, no. 6, pp. 1387–1394, 2016, doi: 10.5958/2249-7315.2016.00292.6.
[65] K. Ghafoor et al., "Bioactive compounds extracted from Saudi dates using green methods and utilization of these extracts in functional yogurt," *Foods*, vol. 12, no. 4, 2023, Art. no. 847, doi: 10.3390/foods12040847.
[66] N. Muñoz-Tebar, C. Muñoz-Bas, M. Viuda-Martos, E. Sayas-Barberá, J. A. Pérez-Alvarez, and J. Fernández-López, "Fortification of goat milk yogurts with date palm (*Phoenix dactylifera* L.) coproducts: Impact on their quality during cold storage," *Food Chemistry*, vol. 454, 2024, Art. no. 139800, doi: 10.1016/j.foodchem.2024.139800.
[67] A. S. Ibrahim, R. Sukor, F. Anwar, S. Murugesu, J. Selamat, and S. Raseetha, "Nutritional, nutraceutical attributes, microbiological and chemical safety of different varieties of dates—A review," *Future Foods*, vol. 10, 2024, Art. no. 100421, doi: 10.1016/j.fufo.2024.100421.
[68] C. P. Mungwari, C. K. King'ondu, P. Sigauke, and B. A. Obadele, "Conventional and modern techniques for bioactive compounds recovery from plants: Review," *Scientific African*, vol. 27, 2025, Art. no. e02509, doi: 10.1016/j.sciaf.2024.e02509.
[69] M. H. Alu'datt et al., "Date palm (*Phoenix dactylifera*) bioactive constituents and their applications as natural multifunctional ingredients in health-promoting foods and nutraceuticals: A comprehensive review," *Comprehensive Reviews in Food Science and Food Safety* , vol. 24, no. 1, pp. 1–40, 2025, doi: 10.1111/1541-4337.70084.
[70] K. Barathikannan et al., "Sustainable utilization of date palm byproducts: Bioactive potential and multifunctional applications in food and packaging," *Food Chemistry*, vol. 482, 2025, Art. no. 144216, doi: 10.1016/j.foodchem.2025.144216.
[71] T. Arumugham, R. Krishnamoorthy, J. AlYammahi, S. W. Hasan, and F. Banat, "Spray dried date fruit extract with a maltodextrin/gum arabic binary blend carrier agent system: Process optimization and product quality," *International Journal of Biological Macromolecules*, vol. 238, 2023, Art. no. 124340, doi: 10.1016/j.ijbiomac.2023.124340.
[72] G. L. Zabot et al., "Encapsulation of bioactive compounds for food and agricultural applications," *Polymers*, vol. 14, no. 19, 2022, Art. no. 4194, doi: 10.3390/polym14194194.
[73] J. AlYammahi et al., "Natural deep eutectic solvents for ultrasonic-assisted extraction of nutritious date Sugar: Molecular screening, experimental, and prediction," *Ultrasonics Sonochemistry*, vol. 98, 2023, Art. no. 106514, doi: 10.1016/j.ultsonch.2023.106514.
[74] K. Afshari, M. J. Dakheli, Y. Ramezan, A. Bassiri, and H. A. Chenarbon, "Physicochemical and control releasing properties of date pit (*Phoenix dactylifera* L.) phenolic compounds microencapsulated through fluidized-bed method," *Food Science and Nutrition*, vol. 11, no. 3, pp. 1367–1382, 2022, doi: 10.1002/fsn3.3173.
[75] K. Afshari, M. J. Dakheli, Y. Ramezan, A. Bassiri, and H. A. Chenarbon, "Effect of microencapsulated date pit (*Phoenix dactylifera* L.) extract on staling and organoleptic properties of Baguette bread," *Journal of Food Science and Technology (Iran)*, vol. 20, no. 144, pp. 227–241, 2024, doi: 10.22034/FSCT.20.144.227.
[76] T. Seerangurayar, A. Manickavasagan, A. M. Al-Ismaili, and Y. A. Al-Mulla, "Effect of carrier agents on flowability and microstructural properties of foam-mat freeze dried date powder," *Journal of Food Engineering*, vol. 215, pp. 33–43, 2017, doi: 10.1016/j.jfoodeng.2017.07.016.
[77] A. D. C. Pech-canul, D. Ortega, A. Garcia-Triana, N. Gonzalez-Silva, and R. L. Solis-Oviedo, "A Brief review of edible coating materials for the microencapsulation of prebiotics," *Coating*, vol. 10, no. 3, 2020, Art. no. 197, doi: 10.3390/coatings10030197.
[78] V. P. Yarlina, A. Diva, Zaida, R. Andoyo, M. Djali, and M. N. Lani, "Ratio variation of maltodextrin and gum arabic as encapsulant on white jack bean tempe protein concentrate," *Current Research in Nutrition and Food Science*, vol. 11, no. 3, pp. 1087–1096, 2023, doi: 10.12944/CRNFSJ.11.3.14.
[79] S. A. Mohamed et al., "Gum arabic: A commodity with versatile formulations and applications," *Nanomaterials*, vol. 15, no. 4, 2025, Art. no. 290, doi: 10.3390/nano15040290.
[80] A. Sultana, S. Aghajanzadeh, B. Thibault, C. Ratti, and S. Khalloufi, "Exploring conventional and emerging dehydration technologies for slurry/liquid food matrices and their impact on porosity of powders: A comprehensive review,"

Comprehensive Reviews in Food Science and Food Safety, vol. 23, no. 3, 2024, Art. no. e13347, doi: 10.1111/1541-4337.13347.

[81] N. Martihandini and N. Handayani, "Effect of carrier materials in foam-mat drying on the flow properties of kombucha tea powder," *Indonesian Journal of Pharmaceutical Education*, vol. 5, no. 2, pp. 168–180, 2025, doi: 10.37311/ijpe.v5i2.29492.

[82] S. Tatasciore et al., "Microencapsulation of hop bioactive compounds by spray drying: Role of inlet temperature and wall material," *Current Research in Food Science*, vol. 8, 2024, Art. no. 100769, doi: 10.1016/j.crfs.2024.100769.

[83] J. Elversson and A. Millqvist-Fureby, "Particle size and density in spray drying - Effects of carbohydrate properties," *Journal of Pharmaceutical Sciences*, vol. 94, no. 9, pp. 2049–2060, 2005, doi: 10.1002/jps.20418.

[84] A. Gharsallaoui, G. Roudaut, O. Chambin, A. Voilley, and R. Saurel, "Applications of spray-drying in microencapsulation of food ingredients: An overview," *Food Research International*, vol. 40, no. 9, pp. 1107–1121, 2007, doi: 10.1016/j.foodres.2007.07.004.

[85] F. R. Eris, S. Kusumasari, V. Y. Pamela, M. R. Febriansah, and R. A. Riyanto, "Dextrose equivalent (DE) variation and maltodextrin concentration effects in yoghurt powder characteristics using foam-mat drying," *Indonesian Food Science and Technology Journal*, vol. 7, no. 1, pp. 36–42, 2023, doi: 10.22437/ifstj.v7i1.30152.

[86] A. Ricci, J. A. A. Mejia, A. Versari, E. Chiarello, A. Bordoni, and G. P. Parpinello, "Microencapsulation of polyphenolic compounds recovered from red wine lees: Process optimization and nutraceutical study," *Food and Bioproducts Processing*, vol. 132, pp. 1–12, 2022, doi: 10.1016/j.fbp.2021.12.003.

[87] H. Habtegebriel, D. Edward, M. Wawire, E. Seifu, and V. Gaukel, "Surface fat and insolubility of whole camel milk powders as affected by spray drying operating parameters," *Food and Bioproducts Processing*, vol. 128, pp. 121–132, 2021, doi: 10.1016/j.fbp.2021.05.001.

[88] P. Mehrali, S. H. Peighambardoust, A. Akbarmehr, and K. Sarabandi, "Insights into selection and application of carbohydrate-based carriers for microencapsulation: Stability and functional properties of maltodextrin, gum Arabic, and β-cyclodextrin in encapsulating tea flower pollen peptides," *Carbohydrate Polymer Technologies and Applications*, vol. 9, 2025, Art. no. 100700, doi: 10.1016/j.carpta.2025.100700.

[89] H. C. F. Carneiro, R. V. Tonon, C. R. F. Grosso, and M. D. Hubinger, "Encapsulation efficiency and oxidative stability of flaxseed oil microencapsulated by spray drying using different combinations of wall materials," *Journal of Food Engineering*, vol. 115, no. 4, pp. 443–451, 2013, doi: 10.1016/j.jfoodeng.2012.03.033.

[90] E. M. Mulcahy, C. W. Park, M. A. Drake, D. M. Mulvihill, and J. A. O'Mahony, "Improvement of the functional properties of whey protein hydrolysate by conjugation with maltodextrin," *International Dairy Journal*, vol. 60, no. 9, pp. 47–54, 2016, doi: 10.1016/j.idairyj.2016.02.049.

[91] M. N. Najafi, R. Kadkhodaee, and S. A. Mortazavi, "Effect of drying process and wall material on the properties of encapsulated cardamom oil," *Food Biophysics*, vol. 6, no. 1, pp. 68–76, 2011, doi: 10.1007/s11483-010-9176-x.

[92] J. A. Pellicer, M. I. Fortea, J. Trabal, M. I. Rodríguez-López, J. A. Gabaldón, and E. Núñez-Delicado, "Stability of microencapsulated strawberry flavour by spray drying, freeze drying and fluid bed," *Powder Technology*, vol. 347, no. 7, pp. 179–185, 2019, doi: 10.1016/j.powtec.2019.03.010.

[93] A. Tolun, Z. Altintas, and N. Artik, "Microencapsulation of grape polyphenols using maltodextrin and gum arabic as two alternative coating materials: Development and characterization," *Journal of Biotechnology*, vol. 239, no. 23, pp. 23–33, 2016, doi: 10.1016/j.jbiotec.2016.10.001.

[94] A. Azman, M. Z. Yusoff, A. Mukhtar, P. Gunnasegaran, N. K. Ching, and A. S. H. Md Yasir, "Application of box-behnken design with response surface methodology to analyse friction characteristics for corrugated pipe via CFD," *CFD Letters*, vol. 15, no. 7, pp. 1–13, 2023, doi: 10.37934/cfdl.15.7.113.

[95] H. Bushnaq et al., "Supercritical technology-Based date sugar powder production: Process modeling and simulation," *Processes*, vol. 10, no. 2, 2022, Art. no. 257, doi: 10.3390/pr10020257.

[96] M. Sobulska and I. Zbicinski, "Advances in spray drying of sugar-rich products," *Drying Technology*, vol. 39, no. 12, pp. 1774–1799,

2021, doi: 10.1080/07373937.2020.1832513.

[97] Sukmawaty, G. M. D. Putra, I. Asmoro, S. Syahrul, and M. Mirmanto, “Heat transfer analysis in fluidized bed dryer with heat exchanger pipe for corn material,” in *IOP Conference Series: Earth and Environmental Science*, 2005, p. 913, doi: 10.1088/1755-1315/913/1/012039.

[98] M. Duran, A. Serrano, A. Nikulin, J. L. Dauvergne, L. Derzsi, and E. Palomo del Barrio, “Microcapsule production by droplet microfluidics: A review from the material science approach,” *Materials and Design*, vol. 223, 2022, Art. no. 111230, doi: 10.1016/j.matdes.2022.111230.

[99] K. Suresh, M. Kumaraswamy, H. Sundaravadanam, V. Kadirvel, V. Thirumavalavan, and N. D. Ganesan, “Engineering perspectives on drying technologies of medicinal plants: A review on kinetic modelling and bioactive compounds retention,” *Applied Science and Engineering Progress*, vol. 19, no. 1, 2026, Art. no. 7900, doi: 10.14416/j.asep.2025.10.003.

[100] N. Muñoz-Tebar, L. Candela-salvador, Á. P, M. Lorenzo, J. Fern, and M. Viuda-martos, “Date (*Phoenix dactylifera* L. cv. Medjool) seed flour, a potential ingredient for the food industry: Effect of particle size on its chemical, technological, and functional properties,” *Plants*, vol. 13, no. 3, 2024, Art. no. 335, doi: 10.3390/plants13030335.

[101] O. J. Airouyuwa, H. Khan, H. Mostafa, P. Mudgil, and S. Maqsood, “A comparative study on sequential green hybrid techniques (ultrasonication, microwave and high shear homogenization) for the extraction of date seed bioactive compounds and its application as an additive for shelf-life extension of Oreochromis niloticus,” *Ultrasonics Sonochemistry*, vol. 111, 2024, Art. no. 107094,doi: 10.1016/j.ultsonch.2024.107094.

[102] S. L. Aguilera-Chávez, T. Gallardo-Velázquez, O. G. Meza-Márquez, and G. Osorio-Revilla, “Spray drying and spout-fluid bed drying microencapsulation of Mexican plum fruit (*Spondias purpurea* L.) extract and its effect on in vitro gastrointestinal Bioaccessibility,” *Applied Sciences (Switzerland)*, vol. 12, no. 4, 2022, Art. no. 2213, doi: 10.3390/app12042213.

[103] A. Falahudin and N. Insin, “Removal of propylparaben in an aqueous system using magnetite-silica ferrofluids of hydrophobic deep eutectic solvent,” *Applied Science and Engineering Progress*, vol. 17, no. 3, 2024, Art. no. 7344, doi: 10.14416/j.asep.2024.03.001.

[104] M. S. Jovanović et al., “Ultrasound-assisted natural deep eutectic solvents extraction of bilberry anthocyanins: Optimization, bioactivities, and storage stability,” *Plants*, vol. 11, no. 20, 2022, Art. no. 2680, doi: 10.3390/plants11202680.

[105] H. Mostafa, J. O. Airouyuwa, and S. Maqsood, “A novel strategy for producing nano-particles from date seeds and enhancing their phenolic content and antioxidant properties using ultrasound-assisted extraction: A multivariate based optimization study,” *Ultrasonics Sonochemistry*, vol. 87, no. 6, 2022, Art. no. 106017, doi: 10.1016/j.ultsonch.2022.106017.

[106] M. Ivanović, M. E. Alañón, D. Arráez-Román, and A. Segura-Carretero, “Enhanced and green extraction of bioactive compounds from Lippia citriodora by tailor-made natural deep eutectic solvents,” *Food Research International*, vol. 111, pp. 67–76, 2018, doi: 10.1016/j.foodres.2018.05.014.

[107] T. Jurić, D. Uka, B. B. Holló, B. Jović, B. Kordić, and B. M. Popović, “Comprehensive physicochemical evaluation of choline chloride-based natural deep eutectic solvents,” *Journal of Molecular Liquids*, vol. 343, 2021, Art. no. 116968, doi: 10.1016/j.molliq.2021.116968.

[108] N. El Husna, E. Noor, F. Fahma, and T. C. Sunarti, “Teknik ekstraksi dan nanoenkapsulasi komponen bioaktif buah malaka: Tinjauan literatur,” *Agrointek : Jurnal Teknologi Industri Pertanian*, vol. 16, no. 2, pp. 171–185, 2022, doi: 10.21107/agrointek.v16i2.12433.

[109] J. Azmir et al., “Techniques for extraction of bioactive compounds from plant materials: A review,” *Journal of Food Engineering*, vol. 117, no. 4, pp. 426–436, 2013, doi: 10.1016/j.jfoodeng.2013.01.014.

[110] J. G. Galvão et al., “Stearic acid, beeswax and carnauba wax as green raw materials for the loading of carvacrol into nanostructured lipid carriers,” *Applied Sciences (Switzerland)*, vol. 10, no. 18, 2020, Art. no. 6267, doi: 10.3390/APP10186267.

[111] M. A. Hashim, X. Huang, L. A. Nadtochii, D. A. Baranenko, M. S. Boulkrane, and T. M. El-Messery, “Encapsulation of bioactive compounds extracted from date palm seeds (*Phoenix dactylifera* L.) and their use in functional food,” *Frontiers in Nutrition*, vol. 9, 2022, Art. no. 1051050, doi: 10.3389/fnut.2022.1051050.

[112] N. A. Abdul-Hamid et al., “Metabolites and biological activities of *Phoenix dactylifera* L. pulp and seeds: A comparative MS and NMR based metabolomics approach,” *Phytochemistry Letters*, vol. 31, pp. 20–32, 2019, doi: 10.1016/j.phytol.2019.03.004.

[113] M. C. Caruso et al., “Evaluation of the oxidative stability of bakery products by OXITEST method and sensory analysis,” *European Food Research and Technology*, vol. 243, no. 7, pp. 1183–1191, 2017, doi: 10.1007/s00217-016-2831-9.

[114] R. Bogusz, M. Nowacka, K. Rybak, D. Witrowa-Rajchert, and E. Gondek, “Foam-mat freeze drying of kiwiberry (Actinidia arguta) pulp: Drying kinetics, main properties and microstructure,” *Applied Sciences (Switzerland)*, vol. 14, no. 13, 2024, Art. no. 5629, doi: 10.3390/app14135629.

[115] S. Aghajanzadeh, A. Sultana, A. Mohammad Ziaiifar, and S. Khalloufi, “Formation of pores and bubbles and their impacts on the quality attributes of processed foods: A review,” *Food Research International*, vol. 188, 2024, Art. no. 114494, doi: 10.1016/j.foodres.2024.114494.

[116] Y. Bai and H. Zhang, “Freeze-enabled synthesis of functional materials: Fundamental, progress, and applications,” *Progress in Materials Science*, vol. 155, 2026, Art. no. 101523, doi: 10.1016/j.pmatsci.2025.101523.

[117] N. Coşkun, S. Sarıtaş, Y. Jaouhari, M. Bordiga, and S. Karav, “The impact of freeze drying on bioactivity and physical properties of food products,” *Applied Sciences (Switzerland)*, vol. 14, no. 20, 2024, Art. no. 9183, doi: 10.3390/app14209183.

[118] W. Bińkowska, A. Szpicer, A. Stelmasiak, I. Wojtasik-Kalinowska, and A. Półtorak, “Microencapsulation of polyphenols and their application in food technology,” *Applied Sciences (Switzerland)*, vol. 14, no. 24, 2024, Art. no. 11954, doi: 10.3390/app142411954.

[119] S. A. Mohamed et al., “Gum arabic: A commodity with versatile formulations and applications,” *Nanomaterials*, vol. 15, no. 4, 2025, Art. no. 290, doi: 10.3390/nano15040290.

[120] A. Ruengdech and U. Siripatrawan, “Improving encapsulating efficiency, stability, and antioxidant activity of catechin nanoemulsion using foam mat freeze-drying: The effect of wall material types and concentrations,” *Lwt - Food Science and Technology*, vol. 162, no. 10, 2022, Art. no. 113478, doi: 10.1016/j.lwt.2022.113478.

[121] M. Kurek et al., “Antioxidants and bioactive compounds in food: Critical review of issues and prospects,” *Antioxidants*, vol. 11, no. 4, 2022, Art. no. 742, doi: 10.3390/antiox11040742.

[122] N. C. Santos et al.,“Microencapsulating *Lacticaseibacillus rhamnosus* GG by spray drying using pea protein, pectin, and tapioca flour: Probiotic viability, digestibility and thermal stability,” *Food and Bioproducts Processing*, vol. 150, pp. 207–216, 2025, doi: 10.1016/j.fbp.2025.01.011.

[123] J. Lee and K. Kim, “Consumer acceptance and perceived sensory characteristics of commercial vegan mayonnaise,” *Foods*, vol. 14, no. 9, 2025, Art. no. 1542, doi: 10.3390/foods14091542.

[124] P. A. Santiago-García et al., “Agavins from Agave potatorum: A low-calorie encapsulant for spray drying of anthocyanins,” *Applied Food Research*, vol. 5, 2025, Art. no. 101289, doi: 10.1016/j.afres.2025.101289.

[125] R. Cahyaningsih, J. M. Brehm, and N. Maxted, “Gap analysis of Indonesian priority medicinal plant species as part of their conservation planning,” *Global Ecology and Conservation*, vol. 26, 2021, Art. no. e01459, doi: 10.1016/j.gecco.2021.e01459.

[126] H. Kamal et al., “Nutraceutical and bioactive potential of high-quality date fruit varieties (*Phoenix dactylifera* L.) as a function of in-vitro simulated gastrointestinal digestion,” *Journal of Pharmaceutical and Biomedical Analysis*, vol. 223, 2023, Art. no. 115113, doi: 10.1016/j.jpba.2022.115113.

[127] S. Y. Al-Okbi, “Date palm as source of nutraceuticals for health promotion: A Review,” *Current Nutrition Reports*, vol. 11, no. 4, pp. 574–591, 2022, doi: 10.1007/s13668-

022-00437-w.

[128] M. Hasan and A. Mohieldein, "In vivo evaluation of anti diabetic, hypolipidemic, antioxidative activities of saudi date seed extract on streptozotocin induced diabetic rats," *Journal of Clinical and Diagnostic Research*, vol. 10, no. 3, pp. 06–12, 2016, doi: 10.7860/JCDR/2016/16879.7419.

[129] L. K. Ong, K. H. Sutikno, K. A. Jodie, and L. Riadi, "Skim coconut milk processing by thermal- and ultrasonic-thermal pasteurization," *Jurnal Rekayasa Proses*, vol. 17, no. 2, pp. 99–103, 2023, doi: 10.22146/jrekpros.82928.

[130] I. A. Agdeppa and J. A. T. Zamora, "The effects of coconut skim milk and coco-dairy milk blend on the nutritional status of schoolchildren," *Journal of Nutrition and Metabolism*, vol. 2022, no. 04, pp. 1–11, 2022, doi: 10.1155/2022/6793866.

[131] A. F. Rosell, E. Marchese, J. Blesa, D. López-malo, A. Frígola, and M. J. Esteve, "Prediction and validation of the solubility of date seed phytosterol using hydrophobic natural deep eutectic solvents," presented at the 5th International Electronic Conference on Foods, University of Valencia, Spain, Oct. 28–30, 2024.

[132] D. J. S. Chong, Y. J. Chan, S. K. Arumugasamy, S. K. Yazdi, and J. W. Lim, "Optimisation and performance evaluation of response surface methodology (RSM), artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS) in the prediction of biogas production from palm oil mill effluent (POME)," *Energy*, vol. 266, 2023, Art. no. 126449, doi: 10.1016/j.energy.2022.126449.

[133] FAO. "Date palm global production in 2024." fao.org. Accessed: Sep. 27, 2025. [Online]. Available: https://www.fao.org/faostat/en/#data/QCL

[134] N. K. Alqahtani, S. A. Ali, and T. M. Alnemr, "Quality preservation of date palm (*Phoenix dactylifera* L.) fruits at the Khalal stage: A review on current challenges, preservation methods, and future trends," *Frontiers in Sustainable Food Systems*, vol. 9, 2025, Art. no. 1558985, doi: 10.3389/fsufs.2025.1558985.

[135] L. Shi, Z. Liu, C. G. Viejo, F. Ahmadi, F. R. Dunshea, and H. A. R. Suleria, "Comparison of phenolic composition in Australian-grown date fruit (*Phoenix dactylifera* L.) seeds from different varieties and ripening stages," *Food Research International*, vol. 181, no. 7, 2024, Art. no. 114096, doi: 10.1016/j.foodres.2024.114096.