

REVIEW | Article in Press

Unravelling the potential of date palm seeds for sustainable biodiesel production

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Received: 31 May 2026 / Accepted: 28 September 2026

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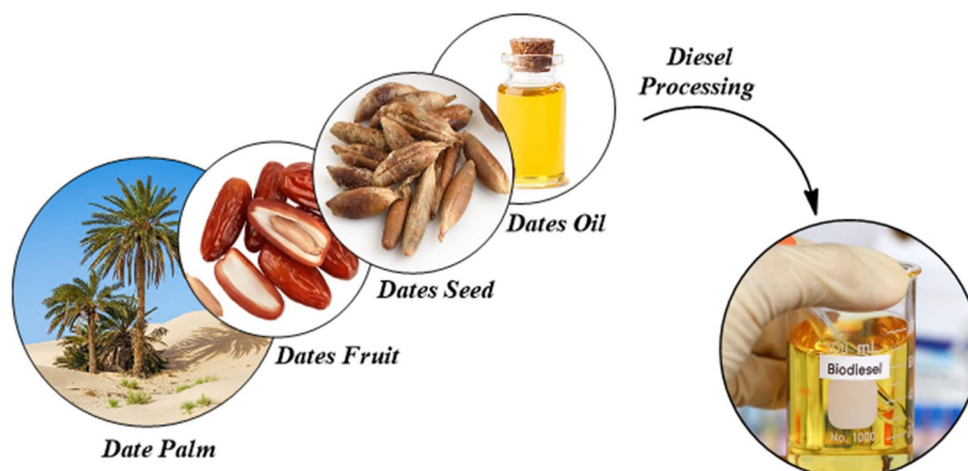
Abstract

The demand for sustainable energy is increasing due to interest in non-edible and waste-derived biodiesel. The date palm is a well-known plant and produces delicious fruit, with its seed often considered a byproduct. It's a powerful source for natural oil production and has unique applications. This review highlights the date palm seeds' potential as a feedstock for biodiesel production, explores advancements in oil extraction and transesterification techniques and evaluates fuel properties along with engine efficacy. Moving beyond conventional overviews, this review also provides a novel and critical analysis of date seed oil (DSO) valorisation, examining a consolidated synthesis of advanced green extraction techniques (ultrasonic and protic ionic liquid recovery), waste-derived/magnetic heterogeneous catalysts, hydroprocessing pathways for bio-jet fuels and green gasoline; quantitative engine emission metrics; fuel property compliance with ASTM D6751 and EN 14,214 standards; and a multi-generational comparative benchmark addressing research gaps in commercial scalability. Its significance is also discussed, including future challenges in feedstock variability, catalyst efficiency, and process scalability. In arid regions, date palm seed biodiesel is a feasible contributor to the bioeconomy and energy security. DSO valorisation supports circular bioeconomy initiatives and low-carbon transportation, particularly in arid date-producing regions.

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Graphical Abstract



Keywords Arab · Catalyst · Extraction · Oil production · Renewable energy

Abbreviations

BTE	Brake thermal efficiency
CO ₂	Carbon dioxide
CO	Carbon monoxide
DS	Date seed
DSs	Date seeds
DSO	Date seed oil
EGR	Exhaust gas recirculation
EGT	Exhaust gas temperature
FAMEs	Fatty acid methyl esters
GHG	Greenhouse gas
HC	Unburned hydrocarbons
HCl	Hydrochloric acid
H ₂ SO ₄	Sulfuric acid
KOH	Potassium hydroxide
LCA	Life cycle assessment
NaOH	Sodium hydroxide
NO _x	Nitrogen oxides
SFC	Specific fuel consumption
TaPa	Tantalum phosphate
TEA	Techno-economic analysis

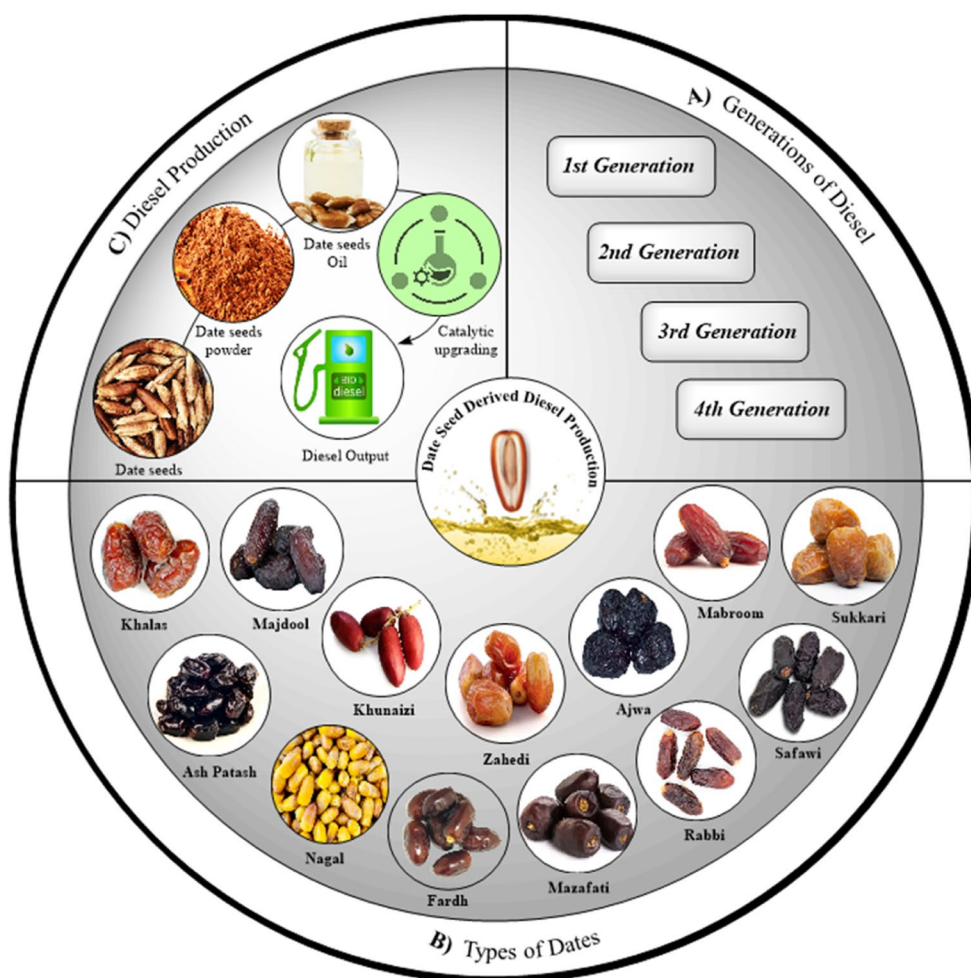
Introduction

Global energy demands are increasing rapidly due to urbanization, population growth and industrial expansion, with the dominant source being fossil fuels despite environmental concerns, i.e., greenhouse gas (GHG) emissions, resource depletion, climate change, and energy insecurity [1, 2]. The transportation sector contributed nearly one-quarter of global CO₂ emissions, highlighting the urgent need for renewable alternatives to conventional

diesel and gasoline [3]. In response, governments, researchers and industries increasingly favor biodiesel as a sustainable energy solution. Among these, biodiesel produced *via* transesterification of oils or fats with alcohol has emerged as a promising substitute for petroleum diesel [4, 5]. It is biodegradable, non-toxic [6–9], renewable and can be used in existing diesel engines with minimal modifications [10–13]. Thus far, the sustainability of biodiesel largely hinges on the choice of feedstock [14]. Biodiesel feedstocks are categorized into four generations (Fig. 1A) [15]. Among these, the second-generation biodiesel derived from non-edible waste-based sources [16] is regarded as more esteemed than the first, third, and fourth generations [17], as they are sustainable and do not compete with food crops. First-generation feedstocks originate from edible crops such as soybean and rapeseed, which have high yields but also lead to food-versus-fuel competition and land use concerns. Second-generation feedstocks are derived from non-edible, waste sources such as lignocellulosic biomass, jatropha and date palm seeds. They are more sustainable since they utilise agricultural residues and reduce dependence on food crops. Third-generation feedstocks are mainly based on microalgae, which are characterised by high lipid contents and rapid growth rates, but they are limited by difficulties in cultivation, harvesting, and cost-efficiency. Fourth-generation feedstocks use genetically engineered organisms and other advanced biotechnological approaches to maximise yield and carbon capture, but are still mainly at the research and pilot stage.

One notable example of a biodiesel feedstock comes from the genus *Phoenix*, which comprises 17 species [18] of date palms worldwide, including *P. dactylifera*, *P. canariensis*, *P. sylvestris*, *P. roebelenii*, *P. reclinata*, *P. theophrasti*, *P. loureiroi*, *P. humilis*, *P. paludosa*, *P. caespitosa*, *P. andamanensis*, *P. acaulis*, *P. pusilla*, *P. rupicola*, *P. chevalieri*, *P. iberica* and *P. atlantica*. The most prominent is *Phoenix dactylifera*, widely cultivated

Fig. 1 DS-derived diesel production: diesel generation (A), types of dates (B), and diesel production (C)



for its sweet, edible dates [19]. It has over 2000 known cultivars globally, and 6000 varieties are recognized for their edible fruits [20]. Some regions have dozens of commercially available cultivars such as medjool, ajwa, mazafati, safawi, zahidi, fardh, khalas, khunaizi, naghal/ nagal, sukkari, mabroom, khasab, ash patash, and rabii, each with distinct taste, texture, and cultural significance (Fig. 1B) [21–23]. Date palms from *Phoenix dactylifera* L [24–26]. are widely cultivated in arid and semi-arid regions, particularly across the Middle East, North Africa, and parts of South Asia due to their adaptability to harsh climates and their economic and nutritional significance [27]. Dates are increasingly recognized for their high nutritional density and therapeutic potential [28], with consumption patterns influenced by regional cultural practices and socioeconomic conditions.

Dates are consumed at distinct ripening stages [29] (i.e., khalal, rutab, and tamar). Date fruit has interesting compounds, namely chelidonic acid [30], which may help protect the fruit from pathogens during ripening and act as an antimicrobial agent. The highest chelidonic acid is extracted when dates are fully ripe and dried [31]. Global date production surpasses 8.53 million metric tons each year [32], and generates vast quantities of agricultural waste, including leaves and seeds [33]. Date seeds (DSs), which account for approximately 10–15% of the fruit's total weight [34, 35], are typically discarded or used as low-value animal feed [36]. DSs demonstrated a notably high polyphenol concentration, surpassing those typically observed in nuts, fruits, and date pulp and are used in various applications, i.e., coffee, soap, biodiesel, bakery, cosmetics, vitamins [37–42] and value-added products, i.e., animal feed, water desalination [43], food industry [44–60], lubricant [61, 62], biocarbon [63], catalyst [64, 65], and packaging films [66]. It has potential anti-inflammatory, antibacterial [67], antioxidant [68–71], and cardiac injury effects [72]. Besides polyphenol content, date seeds contain 5–13% oil [73], making them a viable candidate for biodiesel production (Fig. 1C) [74]. The valorization of DSs into biodiesel offers multiple benefits [75]. It adds value to agricultural waste, reduces environmental pollution, and supports rural economies. Furthermore, this approach supports the principles of the circular economy by converting agricultural waste into valuable energy resources.

Recent research has focused on producing and characterising biodiesel from date seed oil (DSO). Numerous aspects have been reported, including oil extraction techniques (e.g., Soxhlet extraction, solvent-assisted, cold pressing), catalyst selection and optimization (e.g., NaOH, KOH, heterogeneous catalysts), reaction parameters (e.g., temperature, molar ratio, reaction time), fuel properties analysis (e.g., viscosity, flash point, density, calorific value), and engine efficacy testing using biodiesel blends (e.g., B20, B50, B100). These findings are promising at the laboratory scale [76]. There is limited data on the long-term performance of DS biodiesel in real-world engines, as well as its economic viability and environmental footprint at an industrial scale. Furthermore, variations in oil yield and composition across different date cultivars and growing conditions present additional challenges for standardization and scalability.

Despite its nutritional potential [77], date palm [20], date seed [73, 78], and biological activities review [43, 79–84], the field of DS biodiesel as a second-generation biodiesel is less explored [85, 86]. Limited comparative studies of standardized protocols for DS-derived oil extraction and biodiesel synthesis, catalyst performance, reusability, and incentives to support commercialisation. This review highlights updated critical challenges in DS biodiesel production and proposes future research directions. To explicitly differentiate this work from existing general reviews on date palm biology and nutrition, the core novelty of this review lies in four key areas: (i) an updated synthesis of advanced extraction technologies (acoustic cavitation and protic ionic liquids) and engineered heterogeneous catalysts; (ii) detailed mechanistic insights into hydroprocessing and deoxygenation pathways (e.g., *via* tantalum phosphate catalysts) yielding bio-jet fuel and green gasoline; (iii) a consolidated quantitative analysis of engine performance and emission reductions across B5–B100 blends; and (iv) a multi-generational benchmarking matrix evaluating 1st to 4th generation feedstocks while outlining critical gaps in techno-economic analysis (TEA), and life cycle assessment (LCA). By focusing on DSs, a regionally abundant and renewable resource, this review contributes to the broader goal of sustainable energy development, particularly in arid regions where conventional biomass is scarce.

Insights into the chemical composition of date palm oil seed

The date palm of *Phoenix dactylifera* L. is one of the oldest cultivated fruit trees [87]. It has flourished for over 5,000 years, with its origins traced back to ancient Mesopotamia, modern-day Iraq [84] and Egypt [88]. Today, the leading producers include Egypt [89], Saudi Arabia, Iran, Algeria, Iraq, Sudan, Oman [90–92], and the UAE, with India and Pakistan emerging in South Asia [33]. With global date production, the industry generates extensive quantities of agricultural waste, including seeds, spathes, and fronds. It grows in desert agriculture, especially in arid climates, saline soils, and extreme temperatures exceeding 35 °C during fruiting [79, 93, 94]. Drought tolerance and consistent irrigation are necessary for high yields. Propagation is mainly *via* offshoots, ensuring genetic fidelity, while tissue culture is gaining traction for disease-free mass production. Seed propagation is rare due to genetic variability and inferior fruit quality. A mature tree yields 40–100 kg of fruit annually, depending on variety and care [33].

Dates are naturally sweet [95, 96] due to their high content of simple sugars, carbohydrates, primarily glucose and fructose [77], which can constitute over 70–80% of the fruit's dry weight [97]. This concentrated sweetness provides a rapid source of energy and makes dates a popular natural sweetener in functional foods and traditional diets [81]. While DSs, also referred to as pits or kernels, constitute approximately 10–15% of the total fruit weight [98], depending on the variety and maturity of the fruit [99, 100]. Once commonly discarded or used as low-grade animal feed, DSs are now gaining attention for their nutritional content and promising industrial applications [101]. Chemically, DSs are composed primarily of carbohydrates (65–80%, mostly dietary fiber), oil (5–13%), protein (4–6%), moisture (5–10%), and ash (~ 1%) [102]. It also contains a rich array of essential minerals such as potassium, calcium, magnesium, and phosphorus, which contribute to its nutritional value [103–105]. In addition to their macronutrient content, DSs contain significant amounts of polyphenols, flavonoids, and other antioxidants [106], which contribute to their functional properties and oxidative stability [34] (Fig. 2A) [107, 108]. Chemical compositions of date seed and fruit are presented in Table 1 [109].

The oil content of DSs, which ranges from 5 to 13% by dry weight [73], is of particular interest for biodiesel production. The DS oil bioactive compounds and fatty acid profile are presented in Fig. 2B. The high oleic acid (50–55%) [89, 110, 111] content imparted oxidative stability, while other fatty acids, i.e., linoleic acid (18–20%), lauric acid (10%), and palmitic acid (10%) [112] enhanced shelf life and combustion performance [113]. Apart from biodiesel production, DSO has also been used in cosmetic formulations, culinary applications, as well as antimicrobial and antioxidant activities [114].

Extraction and transesterification processes for date seed oil

The production of biodiesel from DSs is initiated with oil extraction, with the oil content of DSs varying according to their maturity, cultivar, and growing conditions [115, 116]. Several oil extraction techniques (including mechanical pressing, solvent extraction, supercritical fluid recovery, and acoustic cavitation) and their corresponding mechanisms are presented in Fig. 3A and B. Effective extraction is vital for enhancing oil yield, alongside environmental sustainability and economic feasibility [117]. Mechanical pressing is an eco-friendly technique that involves physically compressing crushed seeds using hydraulic or screw presses to release oil, avoiding solvents and chemicals [118]. In contrast, solvent extraction [119] employs organic solvents such as ethanol or hexane to dissolve the oil, which is then recovered through evaporation. This method offers a high yield as compared to mechanical pressing. As a green alternative, supercritical fluid extraction has been developed that uses supercritical carbon dioxide (CO₂) as the solvent to produce high-purity oil without toxic residues [120]. However, the expensive equipment and operation limit its application to high-value processes. Regardless of the method used, pretreatment steps such as drying, grinding, and dehulling are essential to increase surface area and improve extraction efficiency [117]. An interesting ultrasonic mechanism reported in Fig. 3B, high-amplitude ultrasonic waves produce forces that fracture seed surfaces, enhance solvent penetration and improve

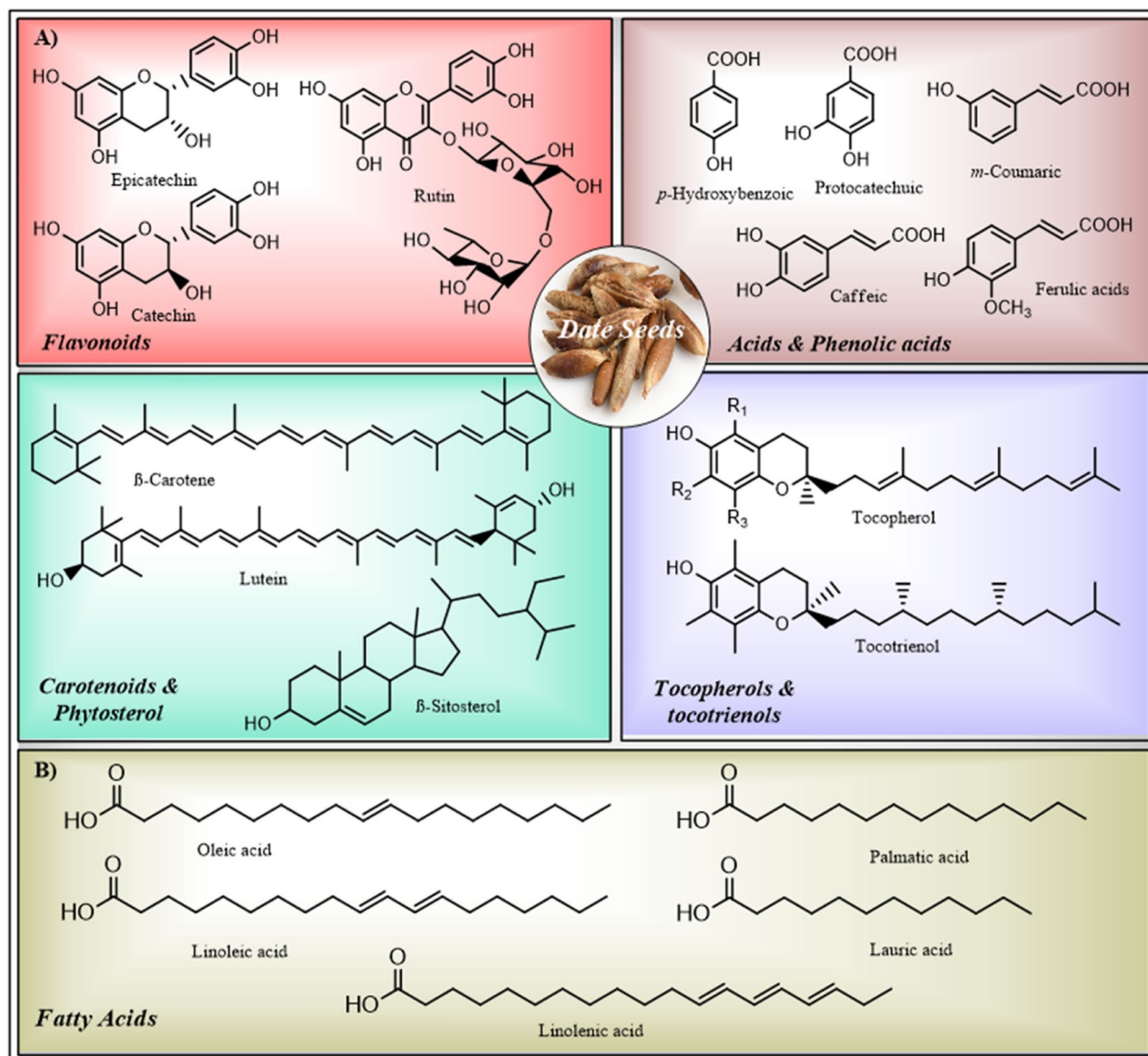


Fig. 2 DSs' primary bioactive components (A) and major fatty acids (B)

intracellular extraction. This collapse also induced intense turbulence, improving solid-liquid mixing and accelerating solute mass transfer [121].

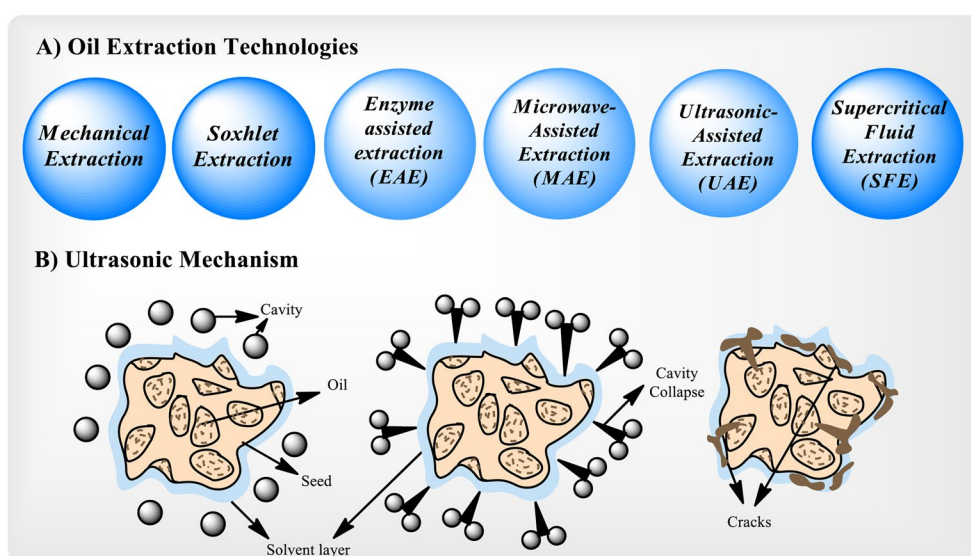
Following oil extraction, the conversion of oil into biodiesel *via* chemical transesterification is presented in Scheme 1 [117, 122, 123]. This reaction breaks down triglycerides, oils, and fats into fatty acid methyl esters (FAMES) to produce biodiesel, with the aid of alcohol and a catalyst [124]. The process also produces a side product named glycerol [113]. Fatty acid methyl and mixed methyl/ethyl esters from date stone oil exhibited superior biodiesel properties compared to ethyl esters, with all biodiesels meeting ASTM standard specifications [119]. DSs biodiesel derived from chemical or enzymatic transesterification showed favorable properties, i.e., low sulfur content, high cetane number, and strong oxidative stability [125], as shown in Table 2. The values indicated good combustion quality, ultra-low emissions, and good storage stability of date seed biodiesel, despite the relatively low oil yield, thus supporting its potential as a sustainable feedstock for biodiesel production. Numerous

Table 1 Chemical compositions of date seed and fruit [109]

Component	Date Seed	Date Fruit
Moisture *	8.64–12.25	9.43–21.53
Protein *	4.81–5.84	1.22–3.30
Fat *	5.71–8.77	0.11–7.33
Ash *	0.82–1.14	1.43–6.20
Carbohydrate *	2.43–4.65	65.7–88.02
Dietary fiber *	67.56–74.20	1.9–16.95
Magnesium #	51.7–58.4	56–150
Calcium #	28.9–38.8	123–187
Phosphorus #	83.6–68.3	12–27
Potassium #	289.6–512	229–293
Sodium #	4.9–8.9	10.25–10.4
Iron #	2.30–2.21	0.3–2.2

(* g/100 g; # mg/100 g)

Fig. 3 Overview of DSO extraction technologies and ultrasonic mechanism. **A** Classification of oil extraction methods including mechanical pressing, Soxhlet extraction, enzyme-assisted, microwave-assisted, ultrasonic-assisted, and supercritical fluid extraction. **B** Schematic representation of the acoustic cavitation/ultrasonic mechanism showing microbubble formation and cavity collapse leading to seed structure disruption and enhanced oil release



Scheme 1 Reaction pathways for DSO transesterification and biodiesel production. Acid- and base-catalyzed reaction pathways showing esterification of free fatty acids (FFAs), transesterification of triglycerides, and potential saponification side-reactions

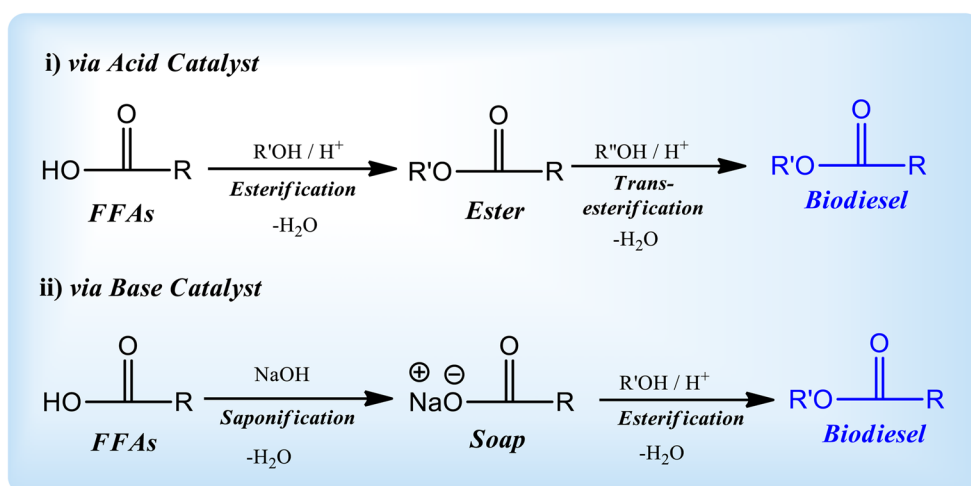


Table 2 Comparative fuel properties of date seed biodiesel

Property	Reported Value	Standard Requirement	Ref
Cetane Number	55–60.3	ASTM D6751 ≥ 47 ; EN 14,214 ≥ 51	[127]
Sulfur Content	< 0.01 wt%	ASTM D6751 ≤ 0.05 wt%	[95]
Oxidative Stability	~ 8 – 10 h (Rancimat, 110 °C)	EN 14,214 ≥ 6 h	[127]
Viscosity (40 °C)	4.2 – 4.6 mm ² /s	ASTM D6751: 1.9 – 6.0 mm ² /s	[127]
Density (15 °C)	~ 0.87 – 0.89 g/cm ³	EN 14,214: 0.86 – 0.90 g/cm ³	[95]

transesterification methods have been reported, each suited to different feedstock characteristics and production goals [126].

Alkaline-catalysed transesterification is commonly used due to its rapid reaction rate and high conversion efficiency. Sodium hydroxide (NaOH) [116] or potassium hydroxide (KOH) [124] is used as a catalyst to facilitate the transesterification reaction. However, this method is highly sensitive to the presence of water and free fatty acids in the oil, which can form soap and then reduce biodiesel yield. For oils with elevated free fatty acid levels, acid-catalysed transesterification is preferred by using hydrochloric acid (HCl) [127] or sulfuric acid (H₂SO₄). It is a more suitable approach, despite being slower and more corrosive than alkaline-based methods. Enzymatic transesterification, using lipase enzymes as biocatalysts, offers an eco-friendly alternative with high product purity and mild reaction conditions. However, expensive enzymes and slower reaction rates restrict their adoption. Catalyst selection and reusability are also significant concerns for biodiesel production.

Transesterification efficiency is affected by several parameters, such as reaction duration (3 h), catalyst amount (4% weight), temperature (75 °C), and alcohol/oil molar ratio (8:1) [14]. Along with biodiesel production, glycerol is also formed as a side product that is separated by an extraction process. The obtained biodiesel is purified to meet international fuel standards like EN 14,214 and ASTM D6751 [128]. The DS's biodiesel production, efficiency, and scalability are mainly improved by oil extraction techniques and transesterification processes [123].

Heterogeneous catalysts such as calcium oxide or those derived from agricultural waste like eggshells or DS ash (i.e., CaO-modified green carbon catalyst [129], CaO-Fe₃O₄ nano-magnetic particles [130], eggshell-derived catalysts [131], Fe₃O₄ NP [132], Ni₃Fe [133], Mn@MgO-ZrO₂ [75] and Ce-Zr/Al-MCM-41 [134]) are being explored for their recyclability, low cost, and environmental benefits. Additionally, novel techniques such as ultrasound-assisted and microwave-assisted transesterification have shown promise in enhancing reaction rates and biodiesel yields while reducing energy input. Among green technologies, ionic liquids utilisation is employed in the lipid and oil extraction domain. These are low-cost and laboratory-prepared, such as [TEA][H₂PO₄] for date seeds to biodiesel production [135].

Biodiesel-grade oils from DSs through Aspen Plus[®] pyrolysis [136] yielded biochar and syngas *via* ionic liquid extraction. Although pyrolysis does not produce biodiesel directly, it generates biodiesel precursors like bio-oil and syngas that can be further upgraded [137, 138]. These approaches showcase DSs as a versatile feedstock in circular biodiesel strategies through green and thermal technologies [136].

Physicochemical Properties of Date Seed Biodiesel

DSO-derived biodiesel exhibits promising physicochemical properties and transesterification reaction parameters, summarized in Table 3 to determine fuel safety, performance, and compliance with international standards such as EN 14,214 and ASTM D6751. DS biodiesel usually has a density and kinematic viscosity of 0.88 g/cm³ and 4.5 – 6.0 mm²/s at 40 °C that meet acceptable limits for diesel engines, respectively. The flash point above 120 °C confirmed safe handling and storage [139], while the pour point (6 – 12 °C) indicated good cold flow properties. The acid value < 1 mg KOH/g reflected minimal free fatty acid content and good oxidative stability. Moreover, the iodine value (~ 60 – 90 g I₂/100 g) measured the degree of unsaturation, stability, and lubricity [140]. The fatty acid profile, especially oleic acid (C18:1), in fuel-supported suitability improves oxidative stability and

Table 3 Parameters, reaction conditions and physicochemical analysis of biodiesel produced from DS

Source / Date / Type	Catalyst	Catalyst amount	Alcohol: oil ratio	Reaction condition	Yield BD (%)	Density* (Kg/m ³)	Kinematic viscosity* (mm ² /s)	Cetane number	Heating values (MJ/kg)	Acid value (mg/KOH/g)	Iodine value (mg/g)	Saponification value (mg/KOH/g)	Ref
ASTM	-	-	-	-	-	860–900	1.9–6.0	≥ 47	~ 37–42	≤ 0.50	N/A	-	[140]
D6751	-	-	-	-	-	860–900	3.5–5.0	≥ 51	~ 37–42	≤ 0.50	≤ 120	-	[113]
EN 14,214	-	-	-	-	-	860–900	3.5–5.0	≥ 51	~ 37–42	≤ 0.50	≤ 120	-	[113]
DS	Mn@ MgO-ZrO ₂	3 wt%	15:1	4 h, 90 °C	96.40	881	3.85	61.12	-	0.11	-	-	[75]
	CaO	4.5 wt%	12:1	120 min, 70 °C	98.20	892	3.98	59.31	-	0.26	-	-	[129]
	CaO-Fe ₃ O ₄	10 wt%	20:1	300 min, 65 °C	69.70	885	3.95	62.67	40.30	-	-	-	[130]
	Eggshells-CaO powder	5 wt%	12:1	1.5 h, 70 °C	93.50	902	4.02	-	-	1.45	-	-	[131]
	Fe ₃ O ₄ NPs	1.5 wt%	15:1	42 min, 55 °C	93.83	889	-	62.20	-	0.46	37.44	224.4	[134]
	Sulfonated biochar	5 wt%	10:1	1.5 h, 90 °C	-	889	4.66	-	-	-	-	-	[141]
	Lipase	8.2 wt%	7.5:1	8 h, 45 °C	92.10	867	3.79	55.00	-	0.11	-	-	[142]
	KOH	1%	6:1	30 min, 65 °C	-	850	3.11	52.00	-	-	-	-	[143]
	Bacteria	16%	4:1	5 h, 70 °C	79.00	890	4.11	47.60	-	0.01	-	-	[144]
	Bi-HAP	5 wt%	12:1	2 h, 64 °C	86.00	845	3.90	49.00	-	0.18	-	-	[145]
	Hydroxyapatite-derived	4 wt%	7:1	3 h, 75 °C	89.00	864	1.90	65.00	-	0.50	120	-	[139]
	Calcined waste fish bones	4.5 wt%	9:1	3 h, 80 °C	89.00	870	3.80	-	-	0.50	-	-	[146]
	KOH	0.21 wt%	6.32:1	70 °C	91.00	870	2.10	-	-	8.97	-	-	[147]
	H ₂ SO ₄	0.5%	6:1	120 min, 50 °C	93.20	869	4.59	65.50	41.27	0.42	48.39	181.1	[148]
	StO-carbon	4%	15:1	90 min, 65 °C	94.27	894	4.61	61.32	-	0.12	-	-	[149]
	Phosphoric acid	0.42 wt%	6:1	4 h, 60 °C	-	-	4.38	62.00	39.80	0.29	-	-	[150]
	Khalas KOH	0.47 wt%	6.1:1	10 min, 52 °C	97.30	870	3.36	-	-	-	-	-	[151]
	Amhat KOH/MeOH	2g/23g	-:3.88	30 min, 30°C	2.05	-	-	60.52	40.50	0.92	88.50	185.4	[152]
	Ramly	-	-:4.48	-	2.43	-	-	55.42	40.14	0.50	75.30	199.0	
	Sewy	-	-:3.34	-	1.90	-	-	57.03	40.18	0.67	90.40	192.5	
	Haiany	-	-:3.31	-	1.84	-	-	54.61	39.84	0.72	86.30	202.3	

* Standardised units for Table 3

combustion efficiency. Linoleic acid (C18:2), palmitic acid (C16:0), and lauric acid (C12:0) also significantly contribute to improving physicochemical properties [135]. Its low sulfur content and absence of aromatic compounds make it an eco-friendly fuel, while a high cetane number (> 50) enhances ignition quality. DS biodiesel performance and sustainability are favorable compared to other non-edible biodiesel sources. These physicochemical characteristics not only validate the DS biodiesel technical feasibility but also highlight its potential for large-scale adoption.

To evaluate the technical compliance and safety of date seed biodiesel, collected physicochemical property data (compiled in Table 3) are systematically benchmarked against international standards ASTM D6751 and EN 14,214. Date seed biodiesel exhibits a density range of 845–902 kg/m³ and kinematic viscosity of 1.90–4.66 mm²/s at 40 °C, satisfying ASTM D6751 (1.9–6.0 mm²/s) and EN 14,214 (3.5–5.0 mm²/s; 860–900 kg/m³) requirements. High cetane numbers (47.6–65.5) comfortably exceed the minimum limits of ASTM D6751 (≥ 47) and EN 14,214 (≥ 51), indicating excellent ignition characteristics. Furthermore, acid values (< 0.50 mg KOH/g) and iodine values (37.4–90.4 g I₂/100 g) conform to EN 14,214 thresholds (≤ 0.50 mg KOH/g and ≤ 120 g I₂/100 g, respectively), confirming low corrosion potential and strong oxidative stability [113, 140].

Recent studies explored several pathways for DS biodiesel conversion (Fig. 4), such as the deoxygenation of fatty acids that proceed through hydrodeoxygenation, decarboxylation, and decarbonylation pathways, influenced by catalyst and reaction conditions. Furthermore, triglyceride deoxygenation pathways, such as γ -H migration, β -elimination, and β - γ carbon scission, are less likely here. The tantalum phosphate (TaPa) catalyst favours γ -H migration and β -elimination, supported by C₁₆ and C₁₈ hydrocarbons in the products. C₁₅ hydrocarbons may form *via* β - γ scission or decarboxylation/decarbonylation of C₁₆ fatty acids. TaPa's acidic sites enable cracking, isomerisation, and cyclisation, producing shorter alkanes, olefins, and cycloalkanes in the biogasoline range. Dehydrogenation on TaPa can also generate aromatics and in situ hydrogen, enriching bio-oil for jet and diesel fuels [153].

Engine performance and emission characterization

The effectiveness of biodiesel in internal combustion engines is a critical factor in determining its practical viability as a renewable energy source. The behavior of DS biodiesel in diesel engines has been studied by using blended compositions such as B20, B50, and B100 without any further modifications. The increment of biodiesel concentration is reported to slightly reduce brake thermal efficiency (BTE) and engine power output due to higher viscosity and lower calorific value of biodiesel as compared to petroleum diesel [154]. For instance, B20 and B50 blends tend to maintain performance levels close to diesel, while B100 exhibited a noticeable decline in efficiency. Furthermore, cylinder pressure and heat release patterns showed only minor deviations, and combustion remained stable across all blends. The exhaust gas temperature (EGT) decreased with higher biodiesel content, suggesting complete combustion and reduced thermal stress on engine components [155].

Date palm seed is a promising feedstock for sustainable fuel, yielding oil up to 10.74 wt% with 92% biodiesel conversion. In Table 4, engine tests across 1600–3600 rpm confirmed that B5-B20 blends deliver reasonable performance and reduced emissions, aligning with global fuel standards and confirming their environmental promise [140, 150]. Interestingly, Zahidi date-derived biodiesel produced *via* ultrasound-assisted transesterification achieved yields of approximately 96.9% within only 5 min, compared to 96.4% in 90 min using conventional heating methods [156]. The resulting biodiesel exhibited improved physicochemical properties, including lower viscosity (3.06 mm²/s at 40 °C), density (~ 0.87 g/cm³ at 25 °C), and higher oxygen content, all of which enhance atomization and combustion efficiency.

DS biodiesel has been identified as a potential replacement for food-based fuels. The combustion and emission characteristics of DS biodiesel have been reported with quantitative values to support its favourable performance. Hellier et al. (2016) showed promising combustion and emission performance at the engine speed of 1200 rpm, with reductions in CO emissions by about 20–25%, and unburned hydrocarbons (HC) emissions by 15–20%, in

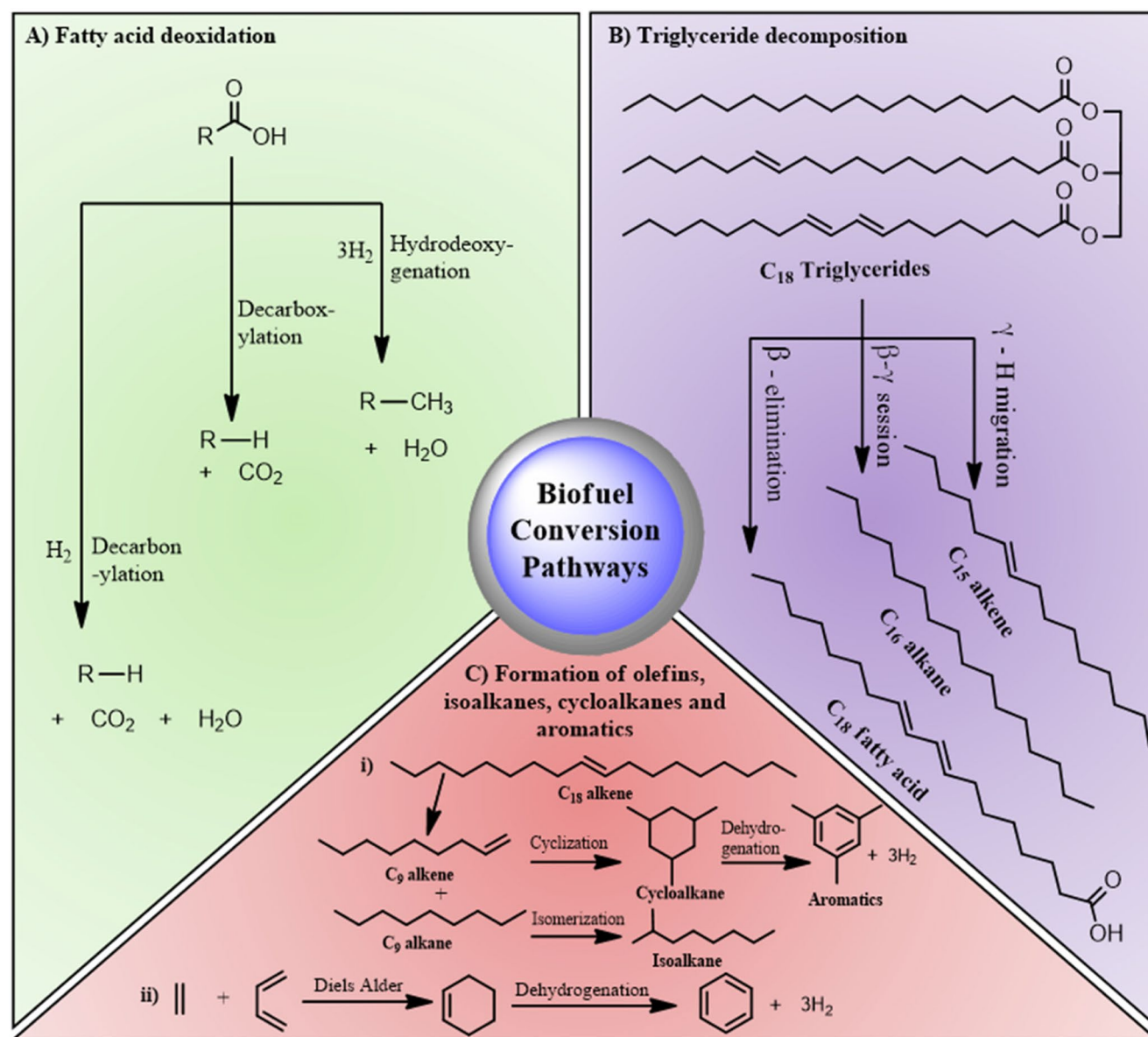


Fig. 4 Conversion pathways of DS biodiesel

Table 4 Fuel properties of biodiesel blends derived from DSO [140]

Blend	Lower Heating Value [MJ/kg]	Density [kg/m ³]	Viscosity [mm ² /s]	Cetane number	C/H Mass ratio	Oxygen Content [wt%]
B5	43.6	839.1	2.7	51.6	6.2	0.6
B10	43.4	842.2	2.8	52.1	6.1	1.2
B15	43.2	845.3	2.9	52.7	6.1	1.8
B20	43	848.4	3.0	53.2	6.0	2.5

comparison to the conventional diesel [113, 156]. The combustion temperature of biodiesel was higher, which resulted in a slight increase of 5–8% in emissions of nitrogen oxides (NO_x), but it was still within acceptable limits [127]. DS biodiesel has the potential to be a sustainable fuel that can enhance engine performance while utilising discarded biomass resources. In a similar way, Azeem et al. (2016) also found that the use of date seed

methyl esters resulted in lower NO_x particulate emissions, longer ignition delay and better burn profiles compared to rapeseed, soybean and conventional diesel. Similarly, Amani et al. (2013) found that DS biodiesel blends improved brake thermal efficiency by 3–5% and decreased the specific fuel consumption (SFC) by est. 2–3% relative to diesel as compared to diesel [95]. These quantitative results indicated that DS biodiesel not only meets international fuel standards, but also improves combustion efficiency and reduces emissions in a quantifiable way [113, 127].

DS biodiesel revealed a significantly cleaner profile in terms of emissions than conventional diesel [155] due to its oxygen-rich nature, which enhanced combustion efficiency, reduced emissions such as carbon monoxide (CO), HC, and particulate matter. For example, B50 and B100 blends can reduce HC and CO emissions by ~ 40%, which is valuable in urban areas to maintain air quality [123]. However, NO_x emissions fluctuated depending on specific conditions, such as a slight increase in NO_x due to higher combustion temperatures and a decrease in NO_x due to exhaust gas recirculation (EGR) or timing adjustments. While carbon dioxide (CO₂) emissions may slightly increase due to the CO₂, offset by the renewable nature of the feedstock, contributed to reducing the overall carbon footprint [123].

To provide a clear, consolidated benchmark against fossil fuels, the comparative performance and exhaust emission profiles of date seed biodiesel blends (B5–B20, B50, and B100) relative to conventional petroleum diesel are summarized in Table 5. While low-level blends (B5–B20) demonstrate enhanced or comparable BTE (+ 3–5%) and lower SFC (–2–3%), higher blend ratios (B50–B100) achieve substantial reductions in harmful emissions (up to 40% reduction in CO and HC) owing to their elevated oxygen content and superior cetane rating [95, 113, 123, 154–156].

Comparative assessment and techno-economic perspectives of date seed biodiesel

Besides physicochemical properties and combustion performance of DS biodiesel, a wider comparative and economic view is required to assess its practical viability. Research on biodiesel has been carried out on a range of feedstocks, including food crops such as soybean and rapeseed, as well as non-edible oils such as jatropha, high-lipid microalgae, and genetically engineered organisms. To position DS biodiesel in this landscape, a comparison of its fuel properties and yields, as well as an assessment of its economic feasibility, TEA, and LCA, is shown in Table 6. This critical assessment offers insight into the competitiveness of DS biodiesel, scalability, and supply chain logistics, which emphasises the potential of DS biodiesel to contribute to sustainable energy transitions.

The comparison of biodiesel feedstocks highlights the uniqueness of date seed biodiesel in the broader context. The potential and limitations of DS biodiesel were highlighted through a comparative assessment of other feedstocks. DS biodiesel is an economic way to valorize the discarded biomass resources and avoid food-versus-fuel conflicts, as in soybean and rapeseed [127]. DS biodiesel has similar fuel properties (cetane number ~ 61–65, sulphur content < 0.01 wt%, oxidative stability ~ 8–10 h) to jatropha and lignocellulosic residues but lower oil yield (5–13% dry weight); hence, extraction and conversion processes need to be optimised [95]. Hellier et al. (2016) reported CO (~ 20–25%), HC (~ 15–20%) and NO_x (~ 5–8%) emission reductions at 1200 rpm, which confirms the favourable combustion characteristics. Economically, TEA of waste-derived biodiesel have shown that the valorisation of waste reduces feedstock costs [161]. Fourth-generation feedstocks are still largely in the research stage, while the DS biodiesel is already technically viable. LCA studies also show that DS biodiesel can reduce greenhouse gas emissions by 50–70% in comparison to fossil diesel [132]. However, research gaps remain in comprehensive TEA and LCA studies of DS biodiesel and comparative engine performance studies with multiple feedstocks. Addressing these gaps is necessary to prove the practical and commercial viability of DS biodiesel in the wider context of biodiesel.

Table 5 Comparative summary of engine performance and exhaust emissions of date seed biodiesel blends relative to petroleum diesel

Parameter	Petroleum Diesel (Baseline)	Low Blends (B5–B20)	Mid Blends (B50)	Pure Biodiesel (B100)	Primary Cause / Mechanism	Ref
Brake Thermal Efficiency (BTE)	Reference (100%)	+ 3% to + 5% or comparable	Comparable to diesel	Slight decline	Higher oxygen content enhances atomization/combustion; offset by lower heating value at B100.	[95]
Specific Fuel Consumption (SFC)	Reference (100%)	-2% to -3% reduction	Slight increase	Moderate increase	Lower calorific value of biodiesel requires higher volumetric fuel mass to maintain load.	[95]
Exhaust Gas Temp. (EGT)	Reference	Comparable	Reduced	Noticeably reduced	Complete combustion and lower energy content reduce thermal stress on components.	[154, 155]
Carbon Monoxide (CO)	Reference (100%)	20–25% reduction	~ 40% reduction	Up to 40% reduction	Higher intrinsic oxygen content facilitates complete oxidation of CO to CO ₂ .	[113, 123, 156]
Unburned Hydrocarbons (HC)	Reference (100%)	15–20% reduction	~ 40% reduction	Up to 40% reduction	Improved fuel oxygenation and higher cetane number reduce unburned fuel fractions.	[113, 123, 156]
Nitrogen Oxides (NO _x)	Reference (100%)	+ 5% to + 8% increase	Minor fluctuation	Slight increase / Fluctuation	Slightly higher peak combustion temperatures; mitigated using EGR or timing adjustment.	[123]

Table 6 Comparative assessment of biodiesel feedstocks

Feedstock	Oil Yield (% dry weight)	Cetane Number	Sulfur Content (wt%)	Oxidative Stability (h)	Economic Feasibility	Sustainability	Ref
Date Seed	5–13	61–65	< 0.01	8–10	• Low-cost • waste valorisation	Utilises discarded biomass, avoids food vs. fuel	[95, 113, 127]
Soybean	18–20	50–52	< 0.05	6–8	• Higher cost • Food crop	Food vs. fuel conflict, land use concerns	[157]
Rapeseed	35–45	52–54	< 0.02	6–7	• Moderate cost	Competes with edible oil markets	[158]
Jatropha	25–30	58–60	< 0.02	7–9	• Low cost • non-edible	Toxic seeds, requires marginal land	[159]
Microalgae	20–50 (varies)	55–60	< 0.01	10–12	• High cost • cultivation/harvesting	High productivity, but scalability issues	[160]
Genetically Engineered Organisms	Varies	60+	< 0.01	> 12	Research stage	Potential for carbon capture. Not commercialized	[113]

Future perspective

DS biodiesel is a sustainable biodiesel, a feasible alternative to fossil fuels, predominantly in date palm agriculture regions. Future research is needed to assess long-term engine durability, optimise fuel injection parameters, and explore hybrid blending strategies with other biodiesel or additives. Eco-friendly DS biodiesel improved air quality and reduced GHG emissions by lowering CO, HC, and SO_x [155]. Moreover, the high oxidative stability of biodiesel is due to its natural fatty acid composition, which enhances its environmental profile by reducing chemical stabilisers. With appropriate policy support and investment in processing infrastructure, DS could play a significant role in advancing to low-carbon transportation, especially in arid and semi-arid regions where date palm waste is abundant and underutilised.

Conclusion

Date palm seeds represent a high-potential second-generation bioenergy feedstock that addresses agro-industrial waste management while offering extensive ecological and economic benefits. DS biodiesel plays a dynamic role in sustainable energy transitions, with continued innovation regarding optimising large-scale production and engine integration. This review demonstrates that DSO, with its high oleic acid composition (50–55%), can be efficiently extracted *via* acoustic cavitation and protic ionic liquid technologies, and converted into FAMES with yields reaching 98.2% using recyclable waste-derived and magnetic heterogeneous catalysts. Its physicochemical properties and sterile combustion profile confirm that DSO biodiesel meets international ASTM D6751 and EN 14,214 fuel specifications. Despite these technical benefits, commercial adoption requires addressing key research gaps, especially in the areas of supply-chain logistics for feedstock collection, long-term engine durability trials, complete TEA, and LCA. Resolving these scalability bottlenecks will allow DSO biodiesel to serve as a sustainable, low-carbon fuel contributor toward regional energy security and GHG mitigation in arid date-cultivating nations.

Acknowledgements None.

Authors' contributions SF contributed to conceptualized, literature review and writing. ZN reviewed and write the manuscript.

Funding None.

Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate Not applicable.

Competing interests The authors declare no competing interests.

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