

Review

Date Palm Biomass as a Feedstock for Renewable Fuels: Catalytic Pathways to Methanol, Ethanol, and Advanced Biofuels

Mohammad Yusuf ^{1,*} , Zaid Abdulhamid Alhulaybi Albin Zaid ¹, Abdulrazak Jinadu Otaru ¹ ,
Abdulrahman Almithn ¹  and Khalad A. AlMuhaysh ² 

¹ Department of Chemical Engineering, College of Engineering, King Faisal University, Al Ahsa 31982, Saudi Arabia; zalhulaybi@kfu.edu.sa (Z.A.A.A.Z.); aotaru@kfu.edu.sa (A.J.O.); aalmithn@kfu.edu.sa (A.A.)

² Department of Mechanical Engineering, College of Engineering, King Faisal University, Al Ahsa 31982, Saudi Arabia; kalmuhaysh@kfu.edu.sa

* Correspondence: myusuf@kfu.edu.sa

Abstract

The present paper highlights a critical assessment of the large-scale production and accumulation of date palm (*Phoenix dactylifera*) by-products. These have been identified as both serious environmental problems and potential renewable energy sources. Landfilling, burning in fields, and other such poor methods are common among many of the countries producing dates as ways to dispose of huge amounts of date palm by-products. The current literature has been assessed for their utilization in energy generation in the form of a circular bioeconomy with respect to the characteristics and composition of date palm seeds, leaflets, rachis and fibers. The study reveals that thermochemical conversion methods such as pyrolysis, gasification and hydrothermal processes are very efficient for the conversion of date palm residues into bio-oil, syngas and biochar. The resulting bio-oils are, however, rich in oxygen, acidic and unstable in nature and need to be upgraded using a catalytic process. Moreover, the review highlights that advanced catalytic technologies can greatly improve the quality of fuel through deoxygenation and the synthesis of hydrocarbons, resulting in the production of “drop-in” gasoline components and SAFs that have characteristics close to those of regular petroleum-based fuels. Also, artificial intelligence- and machine learning-based modeling techniques appear to offer considerable prospects in the realm of thermokinetic studies, process design, and large-scale implementation. Furthermore, the results point out two environmental advantages that accrue from the date palm valorization process, since biochar generated via thermochemical transformation can be used for seawater desalination. Lastly, the techno-economic evaluation and roadmap of future development directions are provided.

Keywords: date palm biomass; biomass conversion; renewable fuels; circular economy; biofuel production



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1. Introduction

1.1. The Global Energy Landscape and the Imperative for Renewables

In the contemporary global energy paradigm, the world relies on energy sources based on oil; as a result, there arise two types of crises associated with such dependence, namely the fast consumption of finite energy sources and negative consequences for the environment due to increased production of greenhouse gases [1]. Hence, the shift to

renewable energy has turned into a vital task rather than a mere theoretical study for energy security. Among various renewable energy sources, biomass takes a prominent position and becomes a perfect solution due to its adaptability and efficiency in solving current environmental problems [2–4].

1.2. The Crisis of Biomass Waste Accumulation

Every year, there is a huge amount of biomass waste that is produced from agricultural, industrial, and urban operations [2,3]. In the past, the biomass residues have been subjected to “end-of-pipe” disposal strategies like dumping in landfills and burning in open pits. This approach has inherent problems as far as sustainability is concerned. The landfilling process creates methane emissions, while the burning process creates particle matter emissions and chemical energy waste [3,5].

Within the agriculture sector, the date palm *Phoenix dactylifera* stands out as an interesting and unexplored biomass source [6,7]. Primarily grown in arid and semi-arid conditions found in Saudi Arabia, the United Arab Emirates, Iran, and Iraq, the date palm sector produces an enormous amount of lignocellulosic waste that cannot be utilized as food material [6,8,9]. In Saudi Arabia, for instance, it is reported that around 15,000 tons of date palm leaf waste are produced annually [10,11]. With the additional amount of biomass waste from other sources, such as seed and fiber production, it can be considered quite large [7,12].

1.3. The “Circular Economy” and the Valorization Perspective

The current review considers the conventional perception of date palm by-products as “waste” as an inadequacy of chemical and economic thinking [5]. However, from the critical perspective, these materials should be perceived as “renewable feedstocks” that could be intentionally recycled back to the process flow [5,13]. The approach towards date palm biomass reutilization through the lens of a circular economy paradigm includes the transformation of low-value waste materials into energy-rich materials like bio-oil, syngas, biochar, and bioethanol [9,10,14].

The inherent value of date palm biomass is determined by the lignocellulosic structure consisting of cellulose, hemicellulose, and lignin, which can be deconstructed and reassembled chemically and biologically [12,15,16]. Unlike first-generation biofuels that compete with food crops for land and water, date palm waste is a non-food, non-salable by-product, making it an ethical and sustainable candidate for large-scale energy production [4,8].

1.4. Thermochemical vs. Biochemical Pathways: A Critical Overview

To achieve exhaustive valorization, several conversion technologies have been developed [4,17]. This paper focuses heavily on thermochemical processes, which utilize heat and pressure to break down complex polymers.

1. **Pyrolysis:** Pyrolysis is the thermal decomposition of biomass without oxygen at temperatures generally in the range of 300–700 °C. During this process, the major lignocellulosic constituents of biomass, namely cellulose, hemicellulose, and lignin, undergo several complex reaction sequences involving depolymerization, fragmentation, dehydration, and recombination, ultimately forming bio-oil, biochar, and non-condensable gases. The product distribution is significantly affected by the operating conditions, i.e., temperature, heating rate, vapor residence time, and type of reactor used.

Based on operating conditions, pyrolysis may be generally classified into two types: slow pyrolysis and fast pyrolysis. Slow pyrolysis involves low heating rates and longer residence times, allowing secondary carbonization reactions, which result in a

maximum yield of biochar. On the other hand, fast pyrolysis is characterized by high heating rates (greater than $100\text{ }^{\circ}\text{C s}^{-1}$) and short vapor residence times (less than 2 s), which facilitate the formation of liquid bio-oil with yields higher than those attained in slow pyrolysis. But, the resultant bio-oil contains high oxygenated contents due to the decomposition of cellulose and lignin, making it chemically unstable, acidic, and energy inefficient. In order to overcome these drawbacks, catalytic pyrolysis is one such method that has been introduced as an upgrade method and facilitates the deoxygenation process in situ, along with enhancing bio-oil quality [14,18].

2. Gasification: Gasification represents a type of chemical process characterized by the conversion of biomass to synthesis gas (syngas) via partial oxidation carried out under elevated temperatures (between 700 and $1200\text{ }^{\circ}\text{C}$). As opposed to a one-off stepwise process, gasification proceeds through multiple stages, namely, drying, pyrolysis, oxidation, and reduction. Several key factors define the nature of the resulting syngas, among them the nature of the equilibrium reactions taking place, which are mainly Boudouard, water–gas, and water–gas shift reactions and play a significant role in the creation of the desired H_2/CO ratio. Other critical elements determining the process are the conditions, namely, the gasifying agent selected. In the case where hydrogen-rich syngas is required, steam gasification is the preferred choice due to the hydrogen enhancement effect of water–gas reactions. However, while air gasification is easier to control, it often leads to nitrogen dilution, reducing the energy content of the resulting syngas. Even though quite versatile, gasification technology is subject to numerous constraints, the major ones being tar formation, difficulties with ash, including ash agglomeration, as well as variations based on biomass differences. Out of the many catalysts tested, nickel-based catalysts have proven to be effective in the decomposition of complex tar molecules to simpler gaseous molecules. Recent experiments with agricultural wastes such as biomass derived from palm have yielded hydrogen yields of greater than 50 vol% under optimized steam gasification conditions. This proves the potential for steam gasification as one of the most promising ways of generating hydrogen gas and integrating it with subsequent processes like the Fischer–Tropsch synthesis [19–22].

A recent techno-economic analysis and simulation model focused on hydrogen production via an integrated steam gasification process combined with a water–gas shift reaction and carbon dioxide capturing unit using waste from date palms. The steam gasification system was capable of hydrogen yields greater than 110 kg h^{-1} with operating temperatures of $850\text{ }^{\circ}\text{C}$. The addition of technologies such as CO_2 removal through methanol absorption and calcium looping increased the hydrogen purity rate. In addition to high hydrogen yields, such an approach was able to demonstrate high energy and exergy efficiencies. This shows how feasible it is to produce hydrogen through the gasification of organic materials [23].

3. Liquefaction and Combustion: The use of hydrothermal liquefaction (HTL) for high-moisture feedstocks has attracted much attention due to the lack of a pretreatment step in the form of drying. HTL takes place in the conditions of subcritical/supercritical water ($250\text{--}374\text{ }^{\circ}\text{C}$, $10\text{--}25\text{ MPa}$), during which water serves not only as a solvent, but as a reactive medium capable of breaking down biomass polymers into fragments via hydrolysis and depolymerization reactions, producing bio-crude oil characterized by lower oxygen concentration than those derived from pyrolysis, however, requiring additional refining steps [24].

The catalyst incorporation has proven indispensable in dealing with certain drawbacks inherent in HTL processes. Homogeneous and heterogeneous catalytic systems enhance bio-crude yield and help reduce oxygen and nitrogen content; how-

ever, catalyst stability and recoverability issues, as well as limited scaling capacity, remain unresolved.

Compared to other thermal conversion methods considered, combustion is an already established, well-known technique for biomass processing; it is quite robust and efficient and thus can be successfully implemented on an industrial scale; however, its thermodynamic efficiency is relatively low, and the range of products produced is limited to low-value energy carriers. Fluidized bed combustion has helped resolve some technical issues in heat recovery and emissions control, yet it remains a low-efficiency method of biomass utilization.

The feasibility of HTL has been demonstrated through continuous processing of wet materials such as sewage sludge and microalgae. In one study, subsequent catalytic hydrotreatment of produced bio-crudes, especially using a two-step approach, led to nearly 92% nitrogen removal efficiency without causing coke formation compared to a single-stage process. This reveals the necessity of upgrading stages in HTL. Even though there are definite benefits of HTL, more efforts should be made to overcome existing technical barriers and improve economic viability [25].

Methods designed for direct energy recovery or the production of liquid intermediates from high-moisture feedstocks.

Furthermore, the integration of advanced pretreatment—such as oil extraction from date seeds—serves as a critical intervention [26,27]. By removing oils for biodiesel before subjecting the remaining lignocellulosic structure to enzymatic hydrolysis or pyrolysis, a “refinery” approach is established [26,28]. This multi-product stream maximizes the energy yield per unit of biomass, ensuring that every fraction of the date palm residue contributes to the bio-economy [29].

1.5. Research Gaps and the Scope of This Review

Even with the rise in studies on agricultural waste products, there is still a glaring void in the scientific knowledge on the comprehensive and multifaceted approach that can be employed to convert the entire anatomical structure of the date palm, especially its leaflets, rachis, fibers, and seeds. As it stands, the existing literature remains fragmented in terms of approaches and techniques, often only considering one mode of conversion or concentrating solely on one biomass form.

This review paper seeks to provide a comprehensive solution by compiling disparate data sets under the umbrella of a circular economy model. The range of this study includes a thorough understanding of the thermokinetics of different segments of the date palm, the assessment of the quality and ageability of the resulting bio-fuels, and a look at catalytic upgrading and advanced computing techniques such as machine learning using kNN analysis.

In addition to these considerations, the study will also include a techno-economic approach to ensure that there is no gap between laboratory success and industrial feasibility.

2. Characterization of Date Palm Biomass

2.1. Proximate and Ultimate Analysis

A comprehensive study of any feedstock for biofuels should start with a chemical fingerprinting of that biomass by means of both proximate and ultimate analyses [12]. From the information provided by documented research works, DTMs and DSs have high volatility rates, which often exceed 70–80%, indicating suitability for thermochemical processing such as pyrolysis [15,30,31]. Moisture plays a crucial role, since high moisture rates can greatly affect the heat value of the biomass feedstocks, as well as the energy needed for its removal [32]. High amounts of carbon and oxygen can be observed in the

result of ultimate analysis; although they contribute positively to energy, they need to be reduced during the upgrading process.

2.2. Anatomical Component Distribution and Lignocellulosic Composition

Not all components of date palm trees are the same; they have different structural properties that determine the way they will degrade during thermal treatment [7,16].

- I. Cellulose and Hemicellulose: This group of polysaccharides is the main source of fermentable sugars and volatile components of bio-oil [33]. As an example, date seeds are well-known for their denser structure and different oil composition than rachis and leaflets [34,35].
- II. Lignin Content: Lignin acts as a robust physical barrier. Its concentration varies significantly across the plant, with fibrous components (e.g., fibers and rachis) typically showing higher resistance to enzymatic and thermal breakdown. High lignin content is often correlated with higher biochar yields during slow pyrolysis [32].
- III. Ash and Fixed Carbon: The inorganic ash content in date palm residues is relatively low compared to other agricultural wastes like rice husks, which is advantageous for reducing reactor fouling and catalyst deactivation in industrial-scale gasifiers [32].

2.3. Energy Content and Variety-Specific Metrics

The higher heating value of biomass represents a typical parameter that describes the inherent energy content and provides information on the applicability of the latter for thermochemical conversion techniques like combustion, pyrolysis, and gasification. As its name implies, the higher heating value reflects the amount of energy released upon combustion, accounting for the latent heat involved in condensing water vapor from the fuel [12].

According to recent studies on date palm varieties in Saudi Arabia, including Sukkari and Khalas, HHV amounts to $\sim 17\text{--}18 \text{ MJ kg}^{-1}$, which is in line with that of conventional biomass types. The specific HHV of biomass depends on several factors, such as its C/H ratio and oxygen concentration. The presence of a large carbon fraction in biomass results in high HHV, whereas increased oxygen levels can lead to partial oxidation and lower the value in question. In other words, lignin fractions are likely to contain more aromatic carbon than cellulose and hemicelluloses and thus have a higher HHV because of a lower O/C ratio [36].

In addition to being used merely as an energy index, HHV plays a significant role in the choice of processes and their efficiencies. In the case of thermochemical processes, the HHV influences their thermal efficiency, as well as the increased syngas calorific value and bio-oil quality at the pyrolysis stage. On the other hand, the lower HHV values coupled with increased oxygen content suggest the necessity of further upgrading, which will add to process complexity and expense. All of these considerations become critical when it comes to distinguishing among various fractions of the date palm biomass [4].

It is important to note that, even though the fruit fraction is abundant in sugars and is thus a good source for fermentation to biofuels such as bioethanol, the lignocellulosic fractions have greater structural stability and energy density. Thus, the “wastes” of the process usually contain high amounts of lignin, and, accordingly, they have higher HHV values and are therefore better suited to be subjected to energy-intensive thermochemical processes.

Additionally, correlations between HHV and ultimate analysis data (carbon, hydrogen, and oxygen content) have been empirically generated, making it possible to quickly calculate the energy density of fuels without resorting to calorific measurements [4]. Such relationships are extremely helpful in assessing biomass materials and designing the pro-

cessing technology. However, one must bear in mind that the energy density is not all there is to fuel quality; ash, volatiles, and reactivity are key factors influencing efficiency.

2.4. Thermal Degradation Profiles (TGA/DTG)

The kinetics of this paper are established on thermogravimetric analysis (TGA) and Derivative Thermogravimetry (DTG). The thermal degradation of date palm biomass can be described through three separate stages:

1. Dehydration: This stage takes place at temperatures under 150 °C; it involves the release of moisture and light volatiles [15].
2. Active Pyrolysis: The main reaction step takes place at temperatures between 200 °C and 450 °C, where the quick degradation of the hemicellulose and cellulose takes place—reflected through the DTG plot [15,37].
3. Passive Pyrolysis: This stage takes place at higher temperatures from 450 °C until 600 °C; it involves the process of gradual charring of the complex lignin system [31,37,38].

Having knowledge about these temperature intervals becomes extremely important when trying to design an effective reactor capable of producing a desired amount of end-products (e.g., bio-oil or syngas) [32,39].

2.5. Critical Comparison of Date Palm Parts

From a critical perspective, the structural heterogeneity of the date palm requires a tailored approach [7,12]. While the leaflets may be more suitable for rapid gasification due to their surface area, the date seeds require intensive pretreatment or specific pyrolysis conditions due to their high density and lignin–oil complex [35,38]. This diversity within a single-tree species underscores the necessity of the “biorefinery” approach advocated in this paper, where each component is directed toward its most efficient conversion pathway [26,29].

3. Pretreatment and Biorefinery Integration Strategies

3.1. The Necessity of Structural Disruption

The inherent resistance of lignocellulosic material restricts effective conversion of date palm waste to fuel or chemicals. In fact, the structure of such material, which is constituted by highly resistant crystalline cellulose microfibrils surrounded by a protective layer of lignin in the presence of hemicellulose, impedes enzymatic activity and transfer of mass/heat during thermochemical processing. Therefore, the pretreatment of materials ought not to be viewed as a preparatory process but, rather, as an integral step controlling the efficacy of subsequent treatment [40–42].

A pretreatment technique is considered effective from the critical perspective if it can disrupt the lignin–carbohydrate complex while preserving fermentable sugars and avoiding the synthesis of inhibitors. The research performed on date palm waste, including seeds and rachis of dates, revealed that increasing the porosity of the material and decreasing cellulose crystallinity can increase the yield of hydrolysis and thermal reactivity [43]. Nevertheless, if chemical or thermal severity increases too much, sugars can start degrading and form inhibitors like furfural or hydroxymethylfurfural (HMF).

3.2. Comparative Pretreatment Modalities

(a) Physical Pretreatment

Size reduction through milling/grinding is essential when dealing with dense biomass like date seeds and rachis. This process ensures an increase in surface area and a decrease in particle size, which in turn increases heat transfer efficiency during thermochemical process-

ing and improves the penetration of reactants during biochemical processing [42]. Nonetheless, this technique is energy-intensive and must be combined with another method.

(b) Alkaline vs. Acid Pretreatment

Date palm waste biomass alkaline pretreatment is well researched due to its high potential for lignin solubilization and cellulose fiber swelling. This process increases digestibility but leads to partial losses of hemicellulose and involves intensive washing, thus requiring excessive use of water and chemicals.

The acid pretreatment (e.g., with diluted H_2SO_4) mainly involves hydrolysis of hemicellulose that gives easily fermentable sugars as products and makes cellulose more accessible. On the other hand, acid media are characterized by a higher probability of the formation of toxic substances like furfural and HMF.

Comparison of two pretreatment methods in terms of lignocellulosic residue degradation shows the following advantages:

- Alkaline pretreatment provides efficient lignin extraction and enzyme action.
- Acid treatment allows obtaining a higher level of hemicellulose solubilization and a rapid reaction.
- The trade-off is related to the degradation of sugars and the efficiency of lignin separation.

Regarding applicability, combined or sequential pretreatment technologies prove highly productive for these processes [41,43].

(c) Organosolv and Solvent-Based Pretreatment

A significant innovation in the valorization of date seeds is the utilization of oil extraction as a primary pretreatment step [27,44]. Organosolv treatment using organic solvents like ethanol and acetone has been recognized owing to its capability to separate biomass into fairly pure cellulose, hemicellulose, and lignin fractions. In date palm waste, the process allows:

- Lignin isolation of high purity (useful for chemicals/materials).
- Formation of fewer inhibitors than in acid processes.
- Catalytic upgrading efficiency improvement.

Comparative data indicate that post-oil-extraction samples exhibit a 75% increase in total sugar production during enzymatic hydrolysis compared to conventional alkaline pretreatment [26]. This is attributed to the fact that oil removal increases the internal surface area and facilitates better penetration of enzymes (such as cellulase) or thermal energy into the lignocellulosic core [26,28].

The process's major drawbacks include solvent recovery and high costs. Nevertheless, organosolv processing is seen more as an important technology for producing value-added biorefineries rather than large-scale fuels.

(d) Microwave-Assisted Pretreatment

Microwave pretreatment is a promising technique for improving biomass breakdown using the principle of volumetric heating. Microwave pretreatment experiments conducted on agricultural biomass (such as palm biomass mimics) have yielded promising results:

- Shortened reaction times.
- Improved lignin breakdown.
- Improved efficacy of enzymatic hydrolysis.

In addition, combinations of microwave heating and chemicals (microwave-alkali pretreatment), especially, have produced positive outcomes, though scale-up issues need to be explored further.

(e) Other Advanced Methods

Steam explosion, ionic liquids, and deep eutectic solvents (DESs) are other alternative pretreatment processes. Although these approaches can achieve high efficiencies in break-

ing down lignocellulose-based materials, issues regarding economic viability and recycling must be addressed.

Pretreatment Selection Criteria for Integrated Date Palm Biorefineries

Considering the viewpoint of biorefinery technology, the choice of the pretreatment method should be guided by the desired final product rather than just by the extent of disruption of the lignocellulosic biomass. In the case of ethanol production and other biochemical processes, the pretreatment stage should ensure the maximum release of sugars without producing harmful substances, such as furfural and hydroxymethylfurfural (HMF). Thus, mild alkaline, organosolv, or even well-controlled acid pretreatments can be utilized. At the same time, the production of bio-oil through pyrolysis requires the goals of reducing the size of particles, improving heat transfer, and releasing volatiles and thermal reactivity, which implies that physical pretreatment methods and moderate demineralization techniques can be enough. As for the gasification process, quality factors of the raw material, such as its moisture content, ash composition, strength, and flowability, will play an important role, since they affect the characteristics of the syngas and tar produced. Finally, for the production of biochar, over-delignification should be avoided, as the lignin plays an important part in producing the charcoal, especially its fixed carbon content.

3.3. Integration Within a “Biorefinery” Framework

The incorporation of these approaches moves the process from being a one-stage transformation to becoming a biorefinery process [29,45]. Under this scenario, the following takes place:

1. First Stage: Physical reduction in size of the date palm components [42].
2. Second Stage: Oil extraction through solvents or mechanical means from the date palm seeds to provide feedstock for biodiesel production [27,44].
3. Third Stage: Application of the “oil-free” solid material for hydrolysis using enzymes to provide bioethanol or for rapid pyrolysis to create bio-oil [14,26].
4. Fourth Stage: Catalytic processing of the resultant liquid materials into green gasoline or jet fuel [46–48].

3.4. Comparative Efficacy

However, based on the data above, it is clear that to ensure “efficient lignin management,” oil extraction is preferred over alkaline pretreatment [27]. Although alkaline pretreatment is characterized by chemical destruction of the material, oil extraction creates an opportunity for physical “opening” of the biomass structure with the removal of 30% of lignin achieved under optimal conditions [26]. In this way, a fully circular procedure will take place, with no loss of seed parts and energy input balanced by biodiesel output.

In conclusion, it is important to state that special attention should be paid to pretreatment procedures depending on the selected part of the date palm. While the fibrous branches can be processed using thermochemical pretreatment, the date seeds should be treated with the proposed oil extraction method first.

Table 1 presents a comparative analysis of different pretreatment processes, including alkaline and acid treatments. The following table gives an insight into the balance between lignin degradation, sugar conversion, inhibitor production, and economics of the process.

Table 1. Comparative analysis of pretreatment strategies for lignocellulosic biomass.

Pretreatment Method	Primary Mechanism	Key Operating Conditions	Advantages	Limitations	Typical Outcomes (Literature)	Suitability for Date Palm Biomass
Alkaline (NaOH, Ca(OH) ₂)	Lignin solubilization and fiber swelling	Mild–moderate temperature (60–150 °C) and long residence time	Effective lignin removal and improved enzymatic digestibility	Chemical consumption, wastewater generation, and hemicellulose loss	Lignin removal up to 40–60% and improved glucose yield	Highly suitable for fibrous fractions (fronds and rachis)
Dilute Acid (H ₂ SO ₄ , HCl)	Hemicellulose hydrolysis and partial cellulose exposure	Moderate–high temperature (120–200 °C) and short residence time	High sugar recovery and fast kinetics	Formation of inhibitors (furfural and HMF) and corrosion issues	Hemicellulose solubilization up to 80–90%	Suitable for carbohydrate-rich fractions and requires detoxification
Organosolv (ethanol, acetone)	Solvent-based lignin extraction and fractionation	Elevated temperature (150–200 °C) and solvent recovery required	High-purity lignin recovery and low inhibitor formation	High cost and solvent recovery challenges	Efficient fractionation into cellulose, lignin, and hemicellulose	Promising for integrated biorefineries
Microwave-assisted	Rapid internal heating and structural disruption	Short time and variable power (300–1000 W)	Reduced reaction time and enhanced penetration	Scale-up limitations and energy efficiency concerns	Improved enzymatic hydrolysis efficiency (~20–40%)	Suitable as a hybrid pretreatment with alkali/acid
Steam Explosion	Thermal + mechanical disruption via pressure release	High pressure (1–3 MPa) and 160–240 °C	No chemicals required and effective fiber disruption	Partial lignin redistribution and inhibitor formation	Increased surface area and moderate sugar recovery	Suitable for bulk residues
Oil Extraction (Date Seeds)	Physical removal of oil and increased porosity	Mechanical/solvent extraction	Dual benefit (biodiesel + pretreatment) and low chemical use	Limited to oil-bearing biomass	Up to ~70% increase in sugar yield post-treatment	Highly suitable for date seeds (unique advantage)

4. Thermochemical Conversion Pathways

4.1. Fundamentals of Thermochemical Transformation and Strategic Selection

Thermochemical conversion represents the most robust technological intervention for the valorization of date palm residues, characterized by the deployment of intensive thermal energy to break down the complex, high-molecular-weight polymers of biomass into manageable energy carriers [17]. Unlike biochemical routes, which are frequently hampered by the slow kinetics of microbial action and the structural recalcitrance of lignin, thermochemical pathways—comprising pyrolysis, gasification, liquefaction, and combustion—offer rapid processing residence times and the unique capability to handle heterogeneous, “real-world” feedstocks [9,18]. From a critical standpoint, the selection of a specific pathway is not arbitrary; it is governed by a precise alignment between the desired end-product (liquid bio-oils, gaseous syngas, or solid biochar) and the feedstock’s specific thermochemical properties.

4.2. Pyrolysis

The thermal degradation of organic compounds in an oxygen-free atmosphere has been named pyrolysis and is the mainstay of recent research work on date palms [14]. This approach tends to be divided into two categories, namely slow and fast pyrolysis. Fast

pyrolysis, however, aims at maximizing liquid product formation from high heating and fast cooling.

4.2.1. Kinetic Parameters and Energy Barriers

In order to convert the process from laboratory experimentation to industry-scale processes, knowledge of the energy barriers for decomposition is essential [39,49]. The studies conducted on different date palm anatomical segments—such as leaflets, rachis, and fibers—with non-isothermal thermogravimetric analysis show that activation energies (E_a) for these parts are between about 148 kJ/mol and 230 kJ/mol [37–39]. The E_a value is obtained by reliable modeling, like the Flynn–Wall–Ozawa (FWO) model and Kissinger–Akahira–Sunose (KAS) model [50]. Interestingly, the composite waste, which can be considered a mixture of different parts of the tree, shows higher thermal stability compared to the separate segments [39]. Thus, in industrial-scale waste collection, it is not always necessary to separate plant parts for maintaining kinetics.

4.2.2. Yield Optimization and Biomass Loading

The results for studies carried out using DTM and DS have shown that the bio-oil yield obtained is significantly affected by the biomass loading rate and reaction time [14,51]. The maximum yield of bio-oil from the DS process is 68 wt%, which occurs at optimally determined conditions (usually within the range of 500 °C to 600 °C), while the yield for the DTM process is around 38 wt% [14,51]. Such a difference is of scientific significance as it reflects the higher energy density of the seed due to its high volatiles.

4.3. Gasification

Beyond mere decomposition, gasification involves the addition of a gasifying substance (for example, air, steam, and/or CO_2) to carry out partial oxidation of the biomass and produce syngas made up of H_2 , CO , CH_4 , and CO_2 [22]. In the case of the date palm seed biomass, a remarkable production of hydrogen is observed via non-catalytic valorization under high temperatures (500–800 °C) [52].

4.3.1. Thermal Promotion of Reforming Reactions

A critical evaluation indicates that an increase in gasification temperature results in an increase in hydrogen and carbon monoxide production since it promotes endothermic steam reforming and water–gas shift reactions [20,22].

4.3.2. Syngas Quality and the Circular Umbrella

The syngas that is produced from the dates' seeds has high calorific content, which makes it ideal for power production through gas turbines or a precursor for methanol synthesis or Fischer–Tropsch liquid fuel synthesis [17]. These multifunctional properties make the date palm biomass directly relevant to the special edition theme of “Renewable Fuels” regarding hydrogen–methanol conversion processes [22].

4.4. Hydrothermal Liquefaction (HTL) vs. Direct Combustion

As much as pyrolysis is efficient in dry residues, hydrothermal liquefaction (HTL) provides a unique process for wet biomass, involving the use of subcritical water as a reactant to yield an excellent bio-crude [24]. Direct combustion, on the other hand, is the oldest technology in this study but perhaps the simplest form of it [10]. Although the technology is already being used in certain areas where there are domestic pellet boilers, in this study, we contend that direct combustion is an efficiency-loss route since it extracts low-grade energy, while pyrolysis and gasification preserve the complexity of the chemical structure of the date palm.

4.5. Reactor Configurations

The effectiveness of thermochemical routes depends intimately upon reactor design [18,53]. Fluidized-Bed Systems benefit from excellent heat and mass transfer properties; key qualities if maximum yield of fuel oils is to be achieved through rapid “pyrolysis.” One novel area of development is the use of concentrated solar energy as the heat input, thereby adding environmental credentials to the process, as burning part of the raw material to generate process heat is not needed [54,55].

Scaling up from laboratory-scale systems (e.g., batch sizes of 500 g) into full industrial-scale operations presents the problem of the production of “tar,” which necessitates the installation of an on-site catalyst zone [17,56].

4.6. Critical Comparative Synthesis

An assessment of the cited data shows that an obvious hierarchy exists. Although gasification can offer the purest energy vector in the form of hydrogen (H₂), fast pyrolysis has been shown to produce the most energy per unit volume using bio-oil. For the case of the Middle East, a combined system that uses dense seeds to produce high-quality bio-oil along with the enormous amount of fibrous fronds to produce syngas would be the most rational solution [10,11].

Table 2 provides a comparison of the studies analyzed for the thermochemical conversion processes in this review, especially those on date palm biomass and its conversion via pyrolysis, gasification, hydrothermal liquefaction, reactor design and scaling up, and application in bioenergy.

Table 2. Comparative assessment of thermochemical conversion pathways for date palm biomass.

Parameter	Pyrolysis	Gasification	Hydrothermal Liquefaction (HTL)	Combustion	References
Operating Temperature (°C)	400–600	500–800 (date seed gasification); up to 1200 in advanced systems	250–374	800–1000	Pyrolysis: [14,39,51]; gasification: [20,22,52]; HTL: [24]; combustion: [10]
Operating Pressure	Atmospheric	Atmospheric–moderate pressure	5–25 MPa	Atmospheric	[22,24]
Feedstock Moisture Requirement	Low (<10–15 wt%)	Low (<15–20 wt%)	High-moisture biomass tolerated	Moderate (<30 wt%)	[14,22,24]
Main Products	Bio-oil, biochar, and syngas	Syngas (H ₂ , CO, CH ₄ , and CO ₂), char	Bio-crude oil, hydrochar, gases, and aqueous phase	Heat, steam, electricity, and ash	[14,17,22,24]
Typical Product Yield	Bio-oil up to 68 wt% (DS); ~38 wt% (DTM)	High syngas yield; enhanced H ₂ production at elevated temperatures	Bio-crude typically 25–45 wt%	Direct thermal energy recovery	[14,22,24,51,52]
Energy Efficiency	High	High	High	Moderate	[10,17,22,24]
Major Advantages	High liquid-fuel yield, biochar co-product, and relatively mature technology	Produces hydrogen-rich syngas suitable for fuels and chemicals	Processes wet biomass without drying; produces energy-dense bio-crude	Technologically simple and commercially mature	[10,17,22,24]

Table 2. Cont.

Parameter	Pyrolysis	Gasification	Hydrothermal Liquefaction (HTL)	Combustion	References
Major Limitations	Bio-oil acidity, instability, and oxygen content require upgrading	Tar formation and gas-cleaning requirements	High-pressure operation and capital cost	Lower biomass valorization and direct CO ₂ emissions	[10,17,22,24,56]
Industrial Maturity	Pilot-to-commercial	Commercially demonstrated	Pilot to early-commercial	Fully commercialized	[10,18,22,24]
Most Suitable Date Palm Fractions	Seeds, leaflets, fibers, and rachis	Seeds, rachis, fibers, and mixed residues	Wet date residues, fruit-processing waste, and moist biomass streams	Fibers, rachis, and mixed pruning residues	[10,14,17,22,24]
Primary End-Use	Biofuels, biochar, and value-added chemicals	Hydrogen, methanol, Fischer–Tropsch fuels, and power generation	Renewable diesel, SAF precursors, and bio-crude	Heat and combined heat-and-power (CHP)	[17,22,24]
Overall Suitability for Date Palm Biorefineries	High	High	Very High	Moderate	[10,17,22,24]

5. Biofuel Production and Product Quality Characterization

5.1. The Multimodal Biofuel Portfolio from Date Palm

The real power of the date palm waste is in the ability to use it as a universal source for producing various forms of energy carriers—from liquid fuel to gas-powered forms and solid carbon-based ones. Importantly, the characteristics of the obtained energy forms, such as their energy content and chemical composition, are not the same but depend on the plant’s anatomical part used as the biomass, as well as the technical parameters of the process of transformation. This chapter focuses on providing a comprehensive comparative review of the three major fuels obtained from *Phoenix dactylifera*—bio-oil, bioethanol, and advanced drop-in fuels (green gasoline/bio-jet) [48].

5.2. Bio-Oil

Bio-oil obtained from fast pyrolysis is a highly complex oxygenated liquid made up of several hundred organic molecules such as phenolic, organic acid, alcohol, and ketone groups.

5.2.1. Yield Optimization and Feedstock Influence

According to the scientific literature, there is a distinct difference in the bio-oil yields from different types of date palm residues. The DS residue gives the highest maximum yield of 68 wt% at an optimized pyrolysis process for 30 min at 500 °C [14]. On the other hand, the DTM residue produces approximately 38 wt% bio-oil [14,51]. The main reason for this variation is due to the high volatiles and low ash percentage in the seed compared to its vegetative counterparts.

5.2.2. The Critical Aging Challenge

The instability of the date palm bio-oil during storage is a notable issue in the successful commercialization of the bio-oil. The process is commonly referred to as aging [57]. This is because aging occurs when secondary reactions like esterification and further polymerization take place, resulting in an increased viscosity and decreased heating value [58–60].

In comparison tests conducted using bio-oils sampled from 15- and 30-day periods, it was noted that although the HHV was comparable (around 28–30 MJ/kg), the excessive amounts of oxygen (over 35%) and water (20%) make it essential to stabilize the bio-oil immediately [61–63].

5.3. Bioethanol

The productivity of the ethanol is greatly impacted by the concentration of sugar, the addition of various additives to the molasses, pH, and a few other parameters. However, despite being well-suited for thermochemical processes, non-salable and waste products from dates—accounting for up to 20% of total produce in significant producing nations—provide a high sugar content source for ethanol production [64].

5.3.1. Fermentation Routes and Sugar Utilization

Given the high levels of glucose and fructose found in wasted dates, direct fermentation with *Saccharomyces cerevisiae* is possible [65]. There is evidence that these fruits are capable of producing ethanol in similar yields to first-generation sources such as corn, without the associated ethical dilemma of “food versus fuel.” [66].

5.3.2. Post-Extraction Valorization

One important innovation in the application of date seeds is in their fermentation after the extraction of the oil from them. Once these date seeds have been deprived of their fat content, they become much more easily subjected to hydrolysis by enzymes [26]. As can be seen from the results, a high amount of fermentable hexoses is released through the enzyme hydrolysis of “oil-free” date seeds [26,64].

5.4. Biodiesel, Green Gasoline, and Bio-Jet Fuel

The conversion of date seed oil to energy-efficient fuel sources is a prime example of top-of-the-line bio-valorization, providing an immediate route for decarbonization of difficult-to-electrify industrial sectors [46,48,67].

5.4.1. Biodiesel via Transesterification

The transformation of date seed oil to fatty acid methyl ester (FAME) is possible with an efficiency range of 7–12% [44,68]. The resulting biodiesel possesses excellent cold flowability characteristics as well as a high cetane number, but it has low oxidative stability [68].

5.4.2. Advanced Hydroprocessing

Beyond the conventional methods of biofuel production, there have been efforts made through the process of hydroprocessing of date seed oil using certain types of catalysts, particularly tantalum phosphate (TaOPO_4), to produce “green gasoline” and “bio-jet fuel” [48]. This procedure entails multiple steps that include hydrodeoxygenation, in which oxygen is stripped away from the fuel as water, isomerization for quality improvement of the fuel, and hydrocracking for carbon chain length C8–C16 [47,69]. Thus, “green gasoline” and “bio-jet fuel” are hydrocarbon fuel products that mimic those of petroleum origins [70].

5.5. Critical Quality Assessment

In terms of critical reviews, the quality of biofuels produced from the date palm should be assessed with respect to petroleum standards. One of the key problems in all streams is the high oxygen to carbon ratio, leading to reduced energy content and corrosiveness [57]. To illustrate, while petroleum diesel possesses an HHV of approximately 45 MJ/kg, raw date palm biofuel only achieves levels between 25 and 30 MJ/kg [14,51]. Consequently,

it can be stated that although the generation of these fuels is technically feasible, their introduction into the world of fuels relies entirely on the techniques highlighted in the following sections of this review.

Further, according to the recently conducted study by Otaru et al. (2025) [71], the results of thermogravimetric analysis (Figure 1) of Date Palm Branch (DPB) biomass show that the main thermal decomposition takes place in the temperature range of 200–530 °C due to hemicellulose and cellulose fraction degradation. In addition to the above, using a kNN model based on machine learning made it possible to predict the behavior of thermogravimetry of DPB, which was characterized by very high accuracy and was confirmed by coefficients of determination (R^2) of 99.8% in the case of the training/validation dataset and 97.5% in the case of the testing dataset [71].

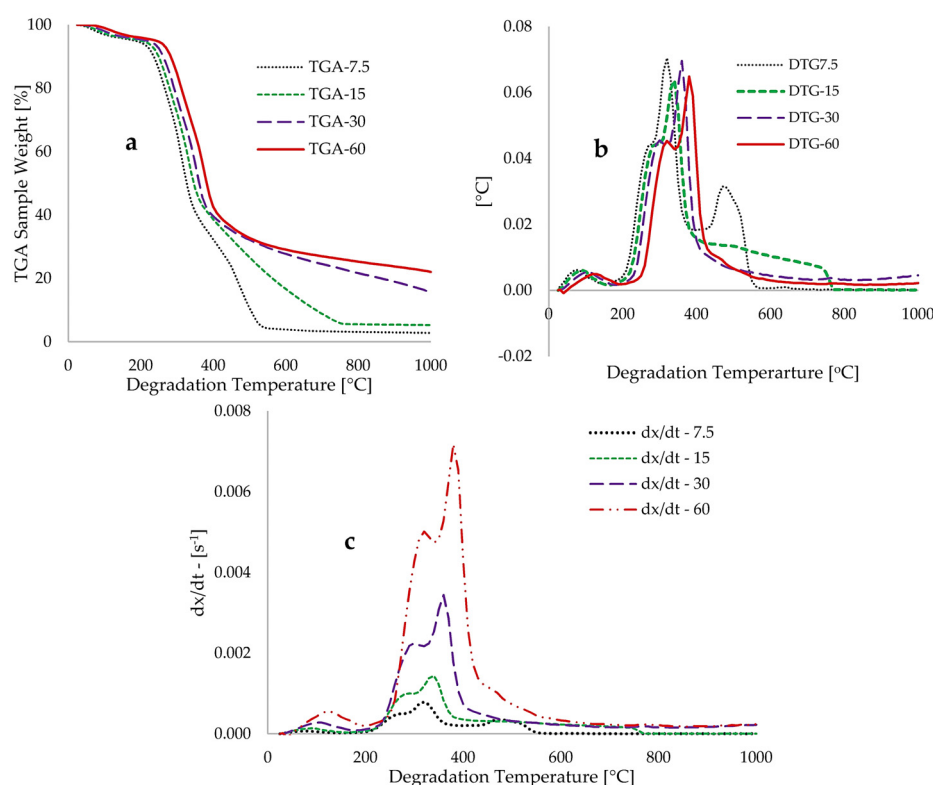


Figure 1. Thermogravimetric (TGA) weight-loss profiles (a), derivative thermogravimetric (DTG) curves (b), and conversion-rate curves (dx/dt) (c) as functions of degradation temperature at various heating rates (Otaru et al. (2025) [71]).

6. Advanced Upgrading and Catalytic Interventions

6.1. The Catalytic Imperative for Bio-Oil Stabilization

Although the thermochemical routes presented in earlier sections have succeeded in converting date palm biomass into its liquid and gas forms, the resultant bio-oil remains intrinsically incompatible with being used within conventional internal combustion engines or refineries [61,72]. In accordance with scientific studies, date palm bio-oil exhibits relatively higher oxygen levels (in excess of 35%), water content, and acidic properties (low pH values) [57,63]. Through a critical review of catalytic upgrading, it is clear that this step is imperative in meeting the prerequisites of energy density and chemical stability in the circular economy [73]. Organic acids and phenols, which are oxygenated compounds, cause the resultant product to be corrosive and unstable when oxidized, thus rendering “drop-in” bio-oil impossible without undergoing complex chemical modifications [74].

6.2. Deoxygenation and Hydroprocessing Mechanisms

Oxygen elimination is the key goal of upgraded fuels; it not only raises the heat content of the fuel but also lowers its corrosiveness [75]. Two prevalent catalytic approaches are discussed in the literature cited:

6.2.1. Catalytic Cracking

Using acidic catalysts like HZSM-5 zeolites to fragment oxygen-rich heavy compounds into lighter aromatic and hydrocarbon molecules [73,76,77]. Such a reaction mechanism has proven efficient for creating gasoline cuts [77]. However, an in-depth investigation shows a key technical constraint: “Coking.” Due to a high level of aromaticity in date palm volatiles, carbon deposits form on active catalyst sites, requiring constant catalyst reactivation [78,79].

6.2.2. Hydro-Deoxygenation (HDO)

This process is the hydrogenolysis of the bio-oil in the presence of certain catalysts, where the oxygen is removed by being converted into water [75]. Research related to the refining of date seed oil focuses on using transition metal catalysts such as Co-MoS₂, Ru/C, or Pt/C to perform this process at very high pressures [75,80]. However, although hydrogenation yields better fuel quality, its major drawback is the high pressure of hydrogen [81].

6.3. Specialized Catalysis

One of the important innovations discussed in the literature is the hydroprocessing of the date palm seed oil on TaOPO₄ catalysts [48]. Unlike common zeolites, TaOPO₄ combines acidic and metallic sites, which results in higher yields of “drop-in” type fuels [48,82].

In order to achieve this result, hydrocracking and isomerization reactions are applied to obtain alkanes (C₅–C₁₂) similar to the components of the commercial petroleum gasoline [48]. One of the most important applications of this technology is bio-jet fuel. Catalytic reaction leads to branched alkanes and cycloalkanes (C₈–C₁₆) needed for high energy density and low freezing points in accordance with aviation standards [48,70]. The successful implementation of the described technology based on hydroprocessing on TaOPO₄ indicates the possibility of the conversion of the low-value date palm waste into high-quality aviation fuel with properties equivalent to Jet A-1 fuel [48,67,83].

6.4. Kinetic Modeling and Multi-Stage Catalytic Zones

The efficiency of these interventions is further understood through kinetic analysis and reactor configuration [73,79]. Research indicates that in situ catalytic pyrolysis—where the catalyst is placed directly in the pyrolysis zone—results in a significantly cleaner bio-oil with reduced tar content compared to non-catalytic runs [73,78]. Critically, multi-stage reactors allow for the separation of the primary decomposition and the secondary catalytic refinement. By adjusting the temperature in the catalytic bed independently of the pyrolysis furnace, researchers have achieved a 20–30% increase in the concentration of aromatic hydrocarbons, which are essential for enhancing the octane rating of the produced fuels [78,79].

6.5. Deactivation and Regeneration

A comprehensive analysis must address the technical bottlenecks of catalysis. The high lignin and ash content in certain date palm parts (like the fibers and rachis) can lead to rapid catalyst fouling [73,79]. The deposition of “coke” blocks the pores of the catalyst, leading to a steady decline in conversion efficiency. Current strategies focus on the regeneration of deactivated HZSM-5 through controlled oxidation. Nevertheless, according to the analysis of the existing literature, a high frequency of regeneration leads to deterioration of the

mechanical properties of catalyst particles. Hence, further work towards the creation of a “coke-resistant” catalyst structure, possibly by the incorporation of mesoporous supports, is highly important for efficient valorization of date palms [81,82].

6.6. Integration of Catalysis in the Biorefinery Framework

In terms of the special “Renewable Fuels” issue, the contribution of catalysis to biomass conversion goes beyond deoxygenation. It also involves possibilities to clean syngas (by tar removal) and to produce methanol/ethanol from streams enriched with hydrogen. Incorporation of such catalytic reactors into the thermochemical conversion reactor forms a “one-pot” biomass processing setup that does not waste energy on cooling-heating cycles and produces a higher yield of valuable hydrocarbons from date palm biomass. Importantly, such an integrated concept fits well into the circular economy scheme by reusing catalysts in closed loops of energy and chemical reactions [13].

The comparative assessment of the catalytic performance of HZSM-5 and TaOPO₄ catalysts shows several significant distinctions in their catalytic action, fuel products, and process operation conditions when converting date palm bio-oil, as compared in Table 3 below.

Table 3. Comparative assessment of HZSM-5 and TaOPO₄ catalysts for upgrading date palm-derived bio-oils.

Comparison Parameter	HZSM-5	TaOPO ₄	Key References
Catalyst Type	Microporous acidic zeolite	Bifunctional acid–metal catalyst	[48,82]
Active Sites	Strong Brønsted acid sites	Combined acidic and metallic active sites	[48,82]
Primary Reaction Pathway	Catalytic cracking and aromatization	Hydrodeoxygenation (HDO), hydrocracking, and isomerization	[48,75,82]
Main Oxygen Removal Mechanism	Cracking and dehydration reactions	Hydrogen-assisted deoxygenation to form water	[75,82]
Target Products	Aromatic hydrocarbons and gasoline-range fuels	Branched alkanes, cycloalkanes, renewable gasoline, and SAF-range hydrocarbons	[48,67,83]
Fuel Quality	High-octane gasoline components	High-quality “drop-in” transportation and aviation fuels	[48,67,83]
Major Advantages	Commercially available, relatively low cost, high aromatic selectivity, well-established industrial use	High deoxygenation efficiency, superior fuel quality, improved selectivity toward aviation-range fuels	[48,82,83]
Major Limitations	Rapid coke formation, pore blockage, frequent regeneration requirements	Higher catalyst cost, dependence on hydrogen supply, and limited industrial deployment	[75,81,82]
Dominant Deactivation Mode	Coke deposition and pore blockage	Gradual loss of active sites and hydrogenation activity	[78,79,81]
Industrial Feasibility	Highly applied in petroleum refining and catalytic cracking units	Moderate; promising but largely at laboratory and pilot scales	[48,81,82]
Overall Suitability	Economical production of aromatic gasoline-range fuels	Production of premium renewable fuels and sustainable aviation fuel (SAF) precursors	[48,67,83]

7. In-Depth Kinetic Modeling and Thermodynamic Analysis

7.1. The Mathematical Foundation of Biomass Decomposition

A critical review of thermochemical conversion requires going beyond qualitative descriptions and delving into the quantitative aspects of physics involved in the process. The process of thermal degradation of various segments of date palm, which include leaflets, rachis, fiber, and seeds, is a kinetic process with stages corresponding to the successive degradation of lignocellulosic components of biomass. Although model fitting is widely used by research scientists, it is important to note that the application of this technique fails to capture the complexity of the concurrent reactions taking place in the biomass matrix [50,84]. Therefore, the adoption of “isoconversional” techniques becomes mandatory [49,85].

The use of thermogravimetric analysis (TGA) at different heating rates, usually 10, 20, 30, and 50 °C/min, will give rise to an estimation of activation energies. By using the models of Flynn–Wall–Ozawa (FWO) and Kissinger–Akahira–Sunose (KAS), activation energy (E_a) values will be obtained for various degrees of conversion [85,86]. From this, it will be observed that degradation reactions are competitive events.

7.2. Activation Energy (E_a) and Structural Recalcitrance

The activation energy plots of various biological tissues in date palm biomass offer valuable information regarding their thermodynamic stability and conversion characteristics. The relatively low activation energy of leaflets (ca. 148–160 kJ/mol) suggests less difficulty breaking bonds and faster devolatilization, owing to their porosity and reduced lignin crystallinity [39]. As far as the process conditions are concerned, this means that leaflet-abundant substrates need less heat input and shorter reaction times, leading to less energy consumption during pyrolysis.

On the other hand, the rachis and seed portions typically have activation energies in excess of 210 kJ/mol, attributable to their high lignocellulosic density and greater lignin content [37,39]. In essence, high activation energies reflect the presence of strong intermolecular bonds and increased structural complexity, requiring more energy to induce breakdown.

It is important to note that comparative kinetic analysis has shown that fluctuations in E_a throughout the conversion stage are reflective of alterations in the predominant decomposition mechanisms. A relatively stable activation energy indicates similar properties of decomposition, while variations in E_a point to various overlapping reactions. Such a finding is especially relevant to date palm biomaterial due to the difference in decomposition reactions linked to cellulose-rich and lignin-rich fractions.

In addition, using a composite material obtained from date palms helps to stabilize the activation energy curve due to the averaging effect between reactive and refractory fractions. From a practical point of view, such an advantage allows one to minimize the variability of feedstock and increase the reliability of thermal processes without prior sorting of the biomass fraction.

7.3. Thermodynamic Parameters: Enthalpy, Entropy, and Gibbs Free Energy

A full assessment of the viability of date palm as a sustainable fuel source would require a discussion of the thermodynamic state functions:

I. Enthalpy (ΔH): ΔH values derived from pyrolysis of date palm biomass are found to be very similar to the respective activation energies, with the gap being less than 6 kJ/mol in most cases. A small difference in these quantities implies that very little extra energy is needed to make an activated complex, hence the possibility of having good properties of thermal conversion. In practical terms, once the process of decomposition starts, its completion becomes easier with minimum energy expenditure [37,39].

II. Entropy (ΔS): As negative ΔS values are recorded in the available literature for these materials, it can be said that the level of ordering of the activated materials is significantly higher than that of the initial state. This is due to the very ordered nature of the “rearrangement” stage during which the highly ordered solids turn into disordered gases/liquids [49,87].

III. Gibbs Free Energy (ΔG): ΔG is positive for all the fractions of date palm biomass, which proves that pyrolysis is not a spontaneous process but is rather endothermic in nature, meaning that it requires an energy supply continuously throughout the process [37]. The value of Gibbs free energy lies in the range of 160–180 kJ/mol, which shows that thermal decomposition can never be self-sustaining without the presence of an external source of energy.

Moreover, according to comparative thermodynamics studies, those biomasses that have smaller ΔG and lesser negative ΔS tend to have better thermal reactivity and reduced operation costs in industrial pyrolysis processes. Hence, in addition to being used as a measure of the feasibility of a reaction, thermodynamic factors can be used for reactor and process optimization [10].

8. Bio-Oil Aging, Stability, and Characterization

8.1. The Physicochemical Complexity of Date Palm Bio-Oil

Although the conversion of DTM and DS into bio-oil could potentially yield a very high conversion of 68 wt% [14,51], the oil obtained at such high conversions is very aggressive and complex in its composition [14,51]. The reasons include acidity (pH down to 2.5), high water content (up to 20%), and the high percentage of oxygen to carbon ratio in the product oil [57,58,63]. From the elemental analysis point of view, although the carbon content is quite high in the oil, it includes a lot of oxygen-containing organic compounds (carboxylic acids, phenols, aldehydes, etc.), making it immiscible with regular petroleum fuels and highly corrosive to metal engines [62].

8.2. The Aging Phenomenon

Among the most important hurdles to the industrial application of date palm biofuels is the phenomenon of “aging” or “instability” in the bio-oil during storage and transportation.

The highly reactive oxygen-containing components in the bio-oil keep undergoing secondary reactions, like esterification and polymerization [59,60]. Studies conducted in the 15 and 30-day period show an increasing trend in viscosity [58–60]. This results in plugging the injectors and filters, necessitating stabilization after production. High moisture content in crude bio-oil results in phase separation, wherein the light aqueous phase (water and low-molecular-weight acids) separates above the heavy organic phase [62,63]. It becomes impossible to pump and atomize such fuel in conventional burners.

8.3. Quality Metrics

The HHV for bio-oil from date seeds is reported to be between 28.5 and 30.0 MJ/kg [14,51]. Although this represents a marked improvement in comparison with that of the biomass feedstock alone (~17 MJ/kg), the HHV is considerably less than that of petroleum-based diesel fuel (~45 MJ/kg) [14]. The reduction in energy content is an inevitable result of oxygen retention in the liquid product [57]. Analysis of this information shows clearly that although the “energy potential” is high, the “energy density” is attainable via catalytic upgradation.

9. Advanced Synthesis of Bio-Jet Fuel and Green Gasoline

9.1. The Hydroprocessing Pathway

The highest form of valorization of date palms is the manufacture of aviation and automobile “drop-in” fuel [67]. Unlike bio-oil, which is an intermediary, green gasoline and bio-jet fuel are hydrocarbons of high quality, capable of being used unmodified. This chapter deals with the hydroprocessing of date seed oil, which is characterized by an unusual lipid profile allowing for this transformation.

One of the most important findings of the research literature concerns the hydroprocessing of date seed oil over Tantalum Phosphate catalysis. In contrast to commonly used zeolites, Tantalum Phosphate catalyst offers a specific ratio of acidity and pore diameter, facilitating three key reactions: 1. Hydro-deoxygenation (HDO). Removing oxygen in the form of water, thereby enhancing the energy content of the fuel; 2. Isomerization. Transformation of linear alkanes into branched isomers. This reaction is a mechanical requirement for bio-jet fuel since branched alkanes possess both the energy content and low melting point (below -47°C) necessary for high altitude flight [88]. 3. Hydrocracking. Transformation of long-chain fatty acids into chains with molecular weights in the range of C8–C16 [83].

9.2. Performance Benchmarking

A critical analysis of the outcomes of this reaction against global standards, such as ASTM D7566, reveals that the biofuel extracted from date palms shares chemical characteristics with Jet A-1 aviation fuel. The success of this reaction confirms that agricultural waste in desert environments can contribute to the reduction of carbon emissions in the aviation industry, which is still technologically impractical to electrify [89,90]. The conversion of a “seed” to “propellant” is considered the most complex and economical use of the date palm circular economy.

10. Integrated “Waste-to-Water” Nexus and By-Product Valorization

10.1. The Circularity of the Water–Energy–Waste Nexus

In terms of the arid zones where date palms grow well, the lack of water is just as important as the need for energy [91,92]. An in-depth analysis would require that one consider the “waste-to-water” relationship whereby products of the thermal and chemical transformation processes are employed in the same ecological environment that generated them [93]. In this regard, this paper examines the use of biochar and syngas as environmental tools rather than merely fuels [94–96].

10.2. Biochar as a Functional Material for Environmental Remediation

This highly porous and functionalized char, which forms about 25–35% of the overall output, cannot be regarded merely as waste material [93]. The porous nature and functionalization of the solid carbonaceous char allow it to function as an excellent adsorbent.

- I. Seawater Desalination and Boron Removal: Amongst the various applications that have been reported, one of the most notable is the utilization of date seed char/biochar in removing boron and boric acid from seawater [92,97]. This is especially useful for desalination facilities in the Middle East because boron is highly resistant to removal by reverse osmosis.
- II. Heavy Metal Sequestration: The biochar obtained from dates’ seeds possesses an impressive ability to bind toxic heavy metals like lead (Pb), copper (Cu), and nickel (Ni) in aqueous solutions [91,94,95]. In many cases, the binding behavior of metal ions onto the surface of date seed biochar is modeled using the pseudo-second order kinetic

equation, which implies strong chemical bonding of ions with oxygen-containing surface groups.

- III. Dye and Organic Pollutant Removal: Nano-activated carbon produced from date palm coir and pits due to its high surface area allows the removal of textile dyes and herbicides, including 2,4-dichlorophenoxyacetic acid, from aqueous solution [96,98]. This “circular” concept suggests that the by-products from the agriculture sector will be used as a means to clean the streams coming from the industry and municipalities.

10.3. Syngas Valorization: Internal Energy and Chemical Synthesis

The gaseous fraction that is formed during gasification and pyrolysis, consisting mainly of H₂, CO, CH₄, and other light hydrocarbons, constitutes the internal “battery” of the biorefinery [19,22].

- I. Hydrogen-Rich Syngas for Energy Self-Sufficiency: Through recycling of the non-condensable syngas back to the reactor used for pyrolysis, it would be possible to create the energy needed for decomposition of the biomass in the form of endothermic heat [20,22]. Such an energy cycle is a hallmark of the circular economy since it helps reduce external energy demands to a minimum.
- II. Precursor for Methanol and Ethanol Synthesis: In connection with the theme “Renewable Fuels”, it should be noted that syngas with a high H₂/CO ratio obtained via gasification of date seeds, especially at temperatures higher than 800 °C, can be efficiently utilized in the production of alcohol [99,100].

10.4. Soil Amendment and Agricultural Sustainability

The return of biochar from date palm to soil closes the biological cycle [93,101,102]. For sandy soils typical of the region, in which the growth of date palms occurs, biochar acts as a constant soil conditioner that improves soil moisture retention, prevents fertilizer losses, and encourages microbial life. As a result, the soil will receive the minerals taken away from it by the trees while growing back into it.

11. Integration of Artificial Intelligence (AI) and Machine Learning in Valorization

11.1. Transitioning to “Industry 4.0” in Bioenergy

The intrinsic complexity and extremely heterogeneous nature of date palm biomass, with variations not just between different anatomical parts (leaflet versus seed), but even amongst geographical cultivars, in terms of lignocellulose ratio, moisture content, and inorganic ash composition, constitute an unrelenting challenge to standardized process control [103]. Typically, optimization of thermochemical variables has occurred via a laborious and costly iterative laboratory process of trial and error [104,105]. The purpose of this section is to analyze the growing necessity of utilizing artificial intelligence (AI) and machine learning (ML) in meeting this complexity [106]. In its critical analysis, the adoption of the “Industry 4.0” approach to bioenergy should be viewed not just as an update to existing processes, but as an entirely new way of thinking about predictive modeling that could help regulate [107].

11.2. Thermokinetic Forecasting via kNN and GBR Analysis

Application of kNN and GBR models in TGA is revolutionizing the understanding of TGA results [108,109]. Through training algorithms using degradation profiles of date palm branch waste, scientists have been able to avoid the constraints posed by conventional kinetics models [108,110].

Although conventional methods, such as the FWO method, give an insight into activation energy, AI models have proved highly accurate in predicting the overall weight loss characteristics over different heating rates (such as 10, 20, or 30 °C/min) [108,109]. These papers indicate that the accuracy of kNN models can be greater than 0.99. One of the important hurdles for biomass pyrolysis is the existence of a kinetic compensation phenomenon due to the variability in pre-exponential factors and activation energy. Algorithms based on AI, especially the GBR approach, have proved highly effective in dealing with such non-linearity and are a sound basis for scale-up of the reactor from small-scale (500 g) to commercial scale [104,108,110].

11.3. Real-Time Optimization of Bio-Oil and Syngas Yields

In addition to kinetic models, machine learning algorithms are extremely useful in achieving maximum yields of products [107,111]. The quality of bio-oil from DTM or DS is very dependent on the interplay of temperature, residence time, and the mass flow of biomass used.

- I. **Dynamic Feedstock Adjustments:** Machine learning programs can be designed to detect changes in the composition of the raw material feed, such as the increase in the fraction of fibrous rachis relative to leaflets, and automatically compensate for the changes in the thermal conditions within the reactor to avoid the decline in the bio-oil yield (which can decrease by more than 50%, down to 38 wt%) [104,110].
- II. **Syngas Composition Control:** In the case of gasification, machine learning programs can optimize the ratio between H₂ and CO molecules. Using real-time measurements of the output from the gasifier, neural networks can control the flow rate of gasification agents (either steam or air) to produce hydrogen-rich syngas required for further reactions (the synthesis of methanol or ethanol) [111,112].

11.4. Computational Catalyst Design and Deactivation Prevention

The cutting-edge catalytic techniques that have been introduced in Section 6, namely the use of tantalum phosphate (TaOPO₄) and zeolites, represent ideal targets for optimization through AI application [104,106].

- I. **Molecular Modeling of Active Sites:** Machine learning can be applied in order to study molecular interactions between oxygenated molecules in the vapor form of bio-oil and the catalytic surface. This can result in the virtual screening of catalyst structure with the aim of finding the most effective combination of pore size and acidity for production of C₈–C₁₆ hydrocarbons (bio-jet fuel), avoiding formation of coke deposits [104,106].
- II. **Predictive Maintenance:** With the help of predictive analytics, AI may predict the deactivation of the catalyst based on the analysis of pressure drop and temperature gradient across the catalyst bed. Such an early warning system will allow for the timely initiation of catalyst regeneration processes, including oxidation of HZSM-5 [103,104].

11.5. Life Cycle Assessment (LCA) and the Economic Barrier

In terms of critical review, the “circular economy” relies heavily on the weakest link within the economy. AI-based TEAs allow for the analysis of thousands of parameters related to the availability of date palm residues, the cost of hydrogen for hydroprocessing, and carbon tax offsets [105,113].

Data-driven life cycle assessments have demonstrated that AI can enable an optimization of the “refinery” concept whereby biofuels can be produced simultaneously; this would lower the carbon footprint of date palm biofuels up to 60% compared to traditional petrofuels [114]. However, the critical analysis should include the significant initial invest-

ment costs (CAPEX) associated with AI integration, which will require financial assistance from the government to make biofuels competitive in the market.

12. Techno-Economic Assessment (TEA) and Circular Economy Framework

12.1. The Economic Feasibility Gap

Any analysis of biomass valorization is ultimately incomplete without a thorough investigation of the economic framework necessary to take laboratory innovations to full-scale implementation. Whereas the technical feasibility of transforming date palm waste into concentrated energy sources is well-established, the path towards commercialization is often hindered by the so-called “Valley of Death,” which refers to the disconnect between the demonstration of proof-of-concept at the pilot scale and viable commercialization [113]. As a matter of critical importance, the main economic limitations do not lie in technical capabilities but rather logistics, particularly in relation to the expense associated with biomass harvesting, the energy consumption inherent to structural pretreatment, and the complex hydroprocessing processes involved in creating drop-in fuels [115]. Techno-economic assessments demonstrate that the profitability of date palm biorefineries is characterized by a critical sensitivity to biomass loading, process integration, and diversification of income sources [113].

12.2. Strategic Integration

The most economically viable method of utilizing date palm—based on comprehensive TEA results—suggests that using just one product (e.g., bio-oil only) is too risky. Given the global nature of crude oil markets, where prices can change suddenly, a single product stream biorefinery may not meet the threshold IRR necessary to draw investment [113].

- I. **The Synergy of Sequential Processing:** As an economic solution, this paper proposes that “total utilization” be considered as a method of mitigating risks. In this scheme, date seeds would undergo biodiesel production (yielding 7–12%), followed by pulp processing through hydrolysis and fermentation for bioethanol [44,64]. The last step, involving the “refined” lignocellulose content, would undergo fast pyrolysis to produce bio-oil. TEA studies indicate that this sequential process will optimize the “value-per-kilogram” ratio of the input material, turning what used to be disposal costs into multiple income streams [10].
- II. **Internal Energy Offsetting:** A crucial economic approach in this context is “thermal coupling” in the biorefinery process. The use of noncondensable syngas and some biochar from the pyrolysis reaction as internal fuel for the drying and reactor processes results in almost complete energy independence. This decrease in OPEX may positively affect the NPV by 30% through improving its stability against fluctuations in energy prices [10].

12.3. Scaling Challenges and the Logistics of Arid Regions

The key issue identified by researchers concerns the substantial difference between laboratory-scale batches of 500 g and industrial-scale needs measured in many tons [53].

For areas that produce huge amounts of agricultural biomass—such as Saudi Arabia, which produces 15,000 tons of date palm leaves per year—the main problem lies in the very low bulk density of the fibrous plant matter [11]. Transportation of unpacked material from a distance becomes impossible from an economic point of view. Importantly, TEA modeling favors a “distributed-centralized” configuration: decentralized torrefaction/pelletization plants producing dense biomass, which is then sent to the centralized refinery facility [115–118].

Despite fast pyrolysis having matured into TRL 7–8 technology, the further development of advanced catalytic hydroprocessing technology to generate “green gasoline” and “bio-jet fuel” continues to be CAPEX-intensive [119]. Due to the high cost of catalyst materials (TaOPO_4 , for example) and the requirement for high-pressure hydrogen for the de-oxygenation process, the cost of SAF production locally is higher than that of conventional petroleum fuels, requiring policy-led carbon credits for competitive parity [90].

12.4. Life Cycle Assessment (LCA) and Carbon Circularity

Moreover, apart from economic considerations, the “circular economy” approach requires an LCA analysis to prove the environmental sustainability of the proposed technology [114,120]. This review argues that the environmental efficiency of biofuel production from date palms is the strongest commercial incentive.

- I. Displaced Methane Emissions: Another important issue to consider during the LCA analysis is “avoided impact.” Replacing conventional methods of managing date palms, such as dumping waste in landfills or open burning, prevents the emission of methane and particulate matter into the atmosphere. The LCA results show that the carbon-neutral process of growing and burning date palms can decrease the GHG emissions by more than 60% relative to the baseline level of fossil fuels [90,114,120].
- II. The Biochar Carbon Sink: Biochar in this context is a physical “carbon sink.” Once placed back into the soil, it serves both purposes of storing carbon over long periods of time and increasing the water-holding capacity of dry soils used for agriculture. The latter is another service offered by ecosystems that can be commoditized in future carbon markets [90,121].

12.5. The “Zero-Waste” Biorefinery

In the comprehensive concept of circular economy, the very existence of the word “waste” is totally excluded [122]. Even the inorganic by-product of gasification, ash, is utilized to produce valuable substances such as silica or as a material to create inexpensive adsorbents for water purification [122]. Most importantly, however, this complete system allows the date palm sector to shift from linear extraction processes to sustainable cycling. Through the synergy of cutting-edge technologies of thermochemical transformation, advanced economic analysis, and environmentally responsible accounting, the date palm, as an important legacy, becomes a high-tech element of the modern renewable energy sector.

13. Integrated Insights and Strategic Roadmaps

13.1. Integrative Summary: The Date Palm Biorefinery Paradigm

In conclusion, this in-depth critical literature review has comprehensively dismantled the transformative capability of the utilization of waste material from date palm (*Phoenix dactylifera*). As such, the focus in this case is the transformation of the problematic nature of agricultural by-products into a vital cornerstone of renewable energy. As indicated in an in-depth evaluation of thermochemical and biochemical processes, the anatomy of the date palm, characterized by volatile seeds, resistant fiber rachis, and lignocellulosic leaflets, does not allow for a general solution. In essence, the data collected and analyzed necessitate the application of multi-modal biorefinery approaches. As highlighted by scientific research synthesized in this review, the use of date seeds as the main ingredient for bio-oil (68 wt%) and hydroprocessed “drop-in” fuel, as well as vegetative pruning residues for hydrogen-based syngas production and biochar, is highly recommended. This is due to the complexity of the plant biomass as shown in Figure 2.

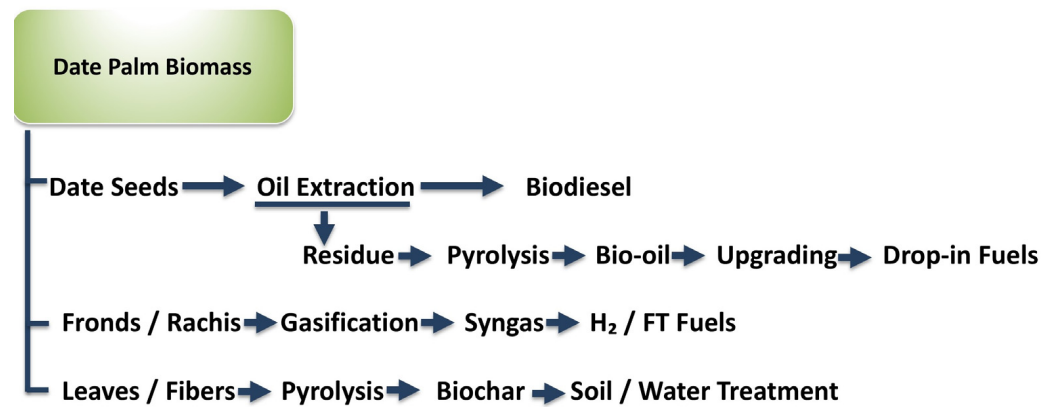


Figure 2. Integrated biorefinery pathways for date palm biomass, highlighting feedstock-specific conversion routes and product diversification.

13.2. Technological Linchpins: Catalysis and Computational Intelligence

The conversion of the oxygen-rich biomass into a suitable aviation fuel depends entirely on the technological advancements, which, in this case, act as mechanical necessities:

- I. **Advanced Catalytic Upgrading:** The introduction of the appropriate catalysts, such as tantalum phosphate and HZSM-5 zeolites, acts as the core necessity for the de-oxygenation and isomerization process. The employment of the catalysts helps in overcoming the natural instability and acid levels of the biofuel derived from the dates and ensures that the energy density and cold flow needs of the current industries are satisfied.
- II. **Industry 4.0 Integration:** The application of artificial intelligence, machine learning (through the use of kNN and GBR algorithms), has been seen as a major breakthrough towards achieving consistency in the production process. Through predictive precision of the thermokinetic properties (greater than 0.99 R^2), artificial intelligence helps in stabilizing the process in spite of the heterogeneity in biomass composition.

13.3. Critical Reflection on the Circular Economy and Water Nexus

Taking a critical perspective on the issue, one cannot separate the concept of “Renewable Fuels” from the larger paradigm of the circular economy. The “Waste-to-Water” combination, wherein biochar as a by-product can be used for desalination and heavy metals elimination purposes, forms a closed system that resolves environmental concerns specific to arid territories. By taking a holistic view on this matter, one is able to create an energy transition model that not only will not hinder food and water security but, moreover, promote their sustainable development. The added value of the by-products is what allows the NPV of the refineries to become even more positive, as these facilities turn out to be ecologically beneficial apart from being profitable. Figure 3 illustrates the addition of energy generation into a closed circle of the water–energy nexus, where the biomass-to-fuel production systems additionally provide auxiliary functions such as water purification and soil enrichment.

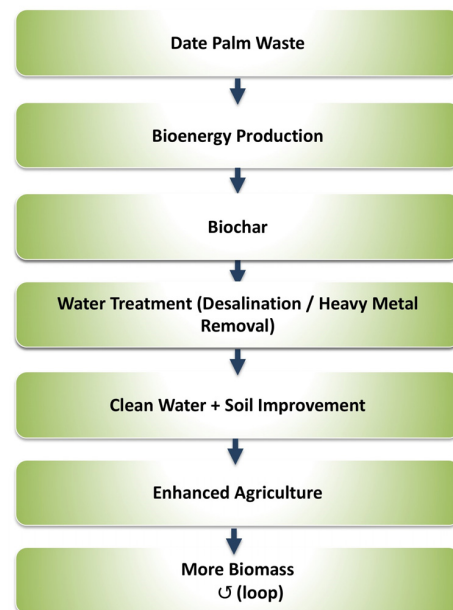


Figure 3. Circular bioeconomy framework integrating energy production with water treatment and agricultural sustainability.

13.4. Strategic Roadmap for Commercial Implementation

Though scientifically feasible, the roadmap leading to the globalization of the markets necessitates a concerted push in certain key frontiers:

- I. **Logistical Densification:** To address the high cost of transport due to the low bulk density of palm fronds, future manufacturing will need to consider decentralized torrefaction and pelletization plants.
- II. **Catalyst Resilience and Lifecycle:** The development of coke-resistant catalyst structures becomes imperative to reduce OPEX, which constitutes a major obstacle to sustainable operation.
- III. **Policy and Carbon Monetization:** To bridge the “Valley of Death” between pilot-scale success and commercial dominance, a robust framework of carbon credits and sustainable aviation fuel (SAF) mandates is essential to align the scientific potential with market-driven profitability.

Figure 4 shows how the strategy roadmap for scaling up the date palm biorefineries from the R&D phase to the commercial phase includes the process stages and barriers that need to be addressed in order to make commercialization a success.

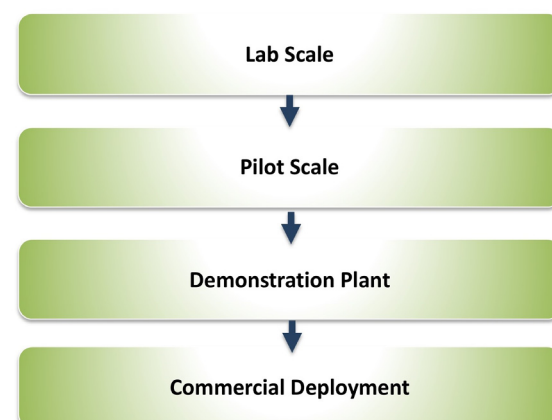


Figure 4. Strategic roadmap for scaling date palm biorefineries from laboratory research to commercial implementation.

14. Conclusions

The current review shows that Phoenix dactylifera waste materials constitute a potential yet largely untapped source of renewable energy. The inherent diversity of date palm waste materials implies the need to consider the type of material used in the conversion processes, whereby the seeds can be used to generate more valuable liquid fuels, whereas the lignocellulosic waste, such as the fronds and rachis, is capable of generating syngas and biochar. In addition, the integration of catalytic technologies and artificial intelligence can optimize the entire process. However, there are several constraints that may prevent the wide-scale adoption of this technology. The variations in the chemical composition of biomass can affect process standardization, whereas expensive processes related to pretreatment, catalytic conversion, and hydrogen recovery make the process economically unviable. The issues, such as catalyst deactivation, inhibitors formed through biochemical conversion, and energy-consuming pretreatment processes, adversely impact the efficiency of conversion processes. Although the conversion of date palm biomass into biofuels has proven to be technically feasible in laboratory settings, further efforts should be made to ensure their commercial applicability by overcoming engineering, economic, and logistical constraints. It will help make date palm wastes a viable source of renewable energy production.

15. Outlook

Future work needs to focus on developing pretreatment processes that consume less energy and are selective in nature, leading to minimal production of inhibitors along with increased access to the biomass. Innovations in the design of catalysts, especially those that are more resistant to coke deposition and can be regenerated, are necessary for effective conversion of oxygenated bio-oils. Process integration must receive greater attention, where thermochemical and biochemical processes can be integrated into modular biorefineries. Artificial intelligence needs to be adopted for online process optimization and scaling up of processes. Moreover, decentralized approaches for densifying the biomass (torrefaction and pelletization) can help overcome problems associated with the supply chain. Techno-economic and life-cycle analysis becomes imperative for assessing the feasibility of the technologies. Lastly, alignment with appropriate policy measures is key.

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