

# Valorization of Date Palm Waste: A Sustainable Route to Second-Generation Bioethanol and Bio-Oil

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**Abstract:** Date palm (*Phoenix dactylifera* L.) is an important tropical fruit growing in North Africa and the Middle East, which is rich in sugar that offer Anaerobic fermentation after steps of treatment to produce bioethanol.

The purpose of the present research is to review the optimal ways to convert date seeds waste into useful products oil, bioethanol, carbon dioxide and fertilizer. Conversion of lignocellulosic agricultural waste into bio-oil, bioethanol and other valuable components will be discussed. These techniques reduce dependence on fossil fuels, emissions of harmful gases and promote the sustainability of natural resources, such as water, and reduce the landfills waste.

This idea encourages investors to invest in energy generation, pharmaceutical industry and other applications from these products. Date seeds are a good source of oil (5 to 13%) so value is added to the feedstock by extracting oil first from the seeds by Soxhlet apparatus and the remaining residue is the feedstock for the second pre-treatment. Utilizing date seeds waste for bioethanol production through *Saccharomyces cerevisiae* grown in yeast.

**Keywords:** *Phoenix dactylifera*, bioethanol, Bio-oil, fermentation, *Saccharomyces cerevisiae*, Soxhlet extraction, Fatty acids.

## 1 Introduction

Global demand for fossil fuel is increasing annually so researchers focused efforts on renewable sources like lignocellulosic biomass which are known as food-based biofuel feedstocks that play an important role in reducing greenhouse emissions [1].

Utilizing biofuels has the potential to significantly reduce Egypt's reliance on imported energy sources, enhance environmental conditions, and give the agricultural sector a new source of revenue [2].

Food crops, crop residues, forest residues, animal wastes, and landfill materials are examples of biological feedstocks that can be used to produce biofuels. The three main types of biofuels that could be produced from these sources are methane, ethanol and biodiesel. Every year, agricultural crops are consumed by humans, livestock, and various industries. A substantial part of these crops is wasted due to improper planting, growing, harvesting, processing and pests damage [3]. The effective utilization of agricultural waste can offer considerable economic and environmental benefits whether through recycling or development of value-added products.

Transforming waste into wealth is the key model in this research. Agricultural waste can be used for various applications, including composting, bioenergy production, bioplastics, construction materials, bio-based chemicals and enzymes, animal feed, natural dyes and cosmetics, soap and detergent production, paper and pulp products, textiles and fibers, biofertilizers, biogas, bioethanol, biodiesel, biochar, and biodegradable packaging [4].

Several agricultural crops have shown strong potential for ethanol production, including corn, rapeseed (canola), sugarcane, palm oil, date palms, soybeans, and many others [5].

Dates are an excellent source of nutrients, especially sugar, which are essential for anaerobic fermentation in bioethanol production. In recent years, both researchers and industry stakeholders have increasingly focused on utilizing agricultural waste as an affordable and scalable feedstock for bioethanol generation. Among these waste materials, date palm seeds powder residues, as shown in Figure 1, stand out as one of the most abundant agricultural by-products and present a cost-effective option for sustainable ethanol production [6].

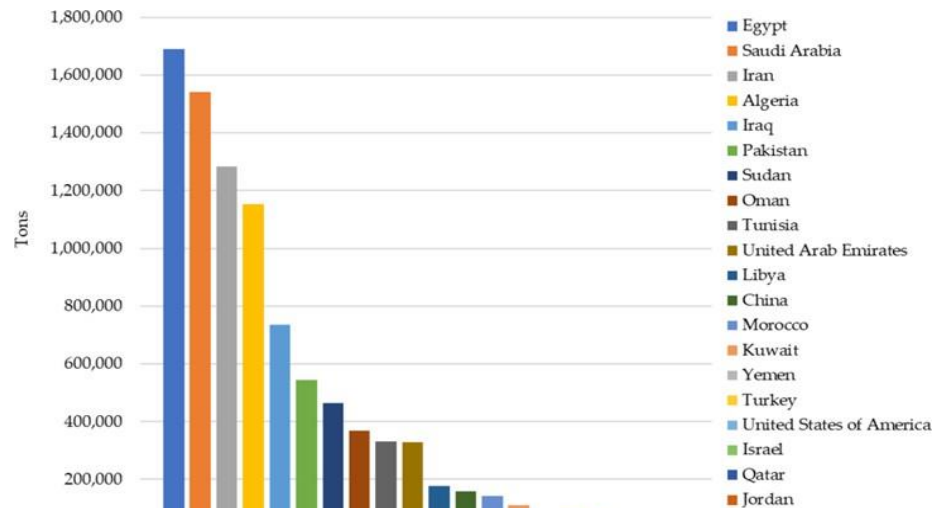


**Fig. 1:** Date Seeds Powder [6]

Accordingly, this study aims to evaluate the potential use of date palm waste as a viable feedstock for bioethanol production.

Investment in sustainable development, particularly in the conversion of waste biomass into renewable bio-based products, is driven by the urgent need to meet the needs of current generations without compromising the ability of future generations to meet theirs. As sugar-based ethanol production is already a well-established and widely studied technology, current research efforts are increasingly focused on converting cellulosic biomass into fermentable sugars and exploring innovative, non-traditional technologies for ethanol production [7].

For almost 5000 years, the date palm (*Phoenix dactylifera* L.) has been one of the oldest cultivated fruit crops in North Africa and the Middle East. It most likely originated in the Middle East's arid subtropical deserts around present-day Iraq and Iran. It was most likely domesticated and grown in that region around 5000 years ago, before spreading to Egypt around 3500 years ago (before the modern era) and India, western North Africa, and Southern Europe by 2000 years ago [8]. Figure 2 presents a list of the world's leaders in date production. The figure shows that Egypt is the world's top producer.

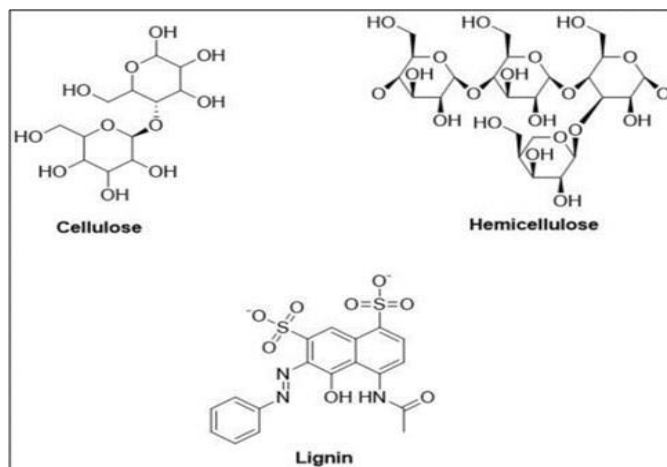


**Fig. 2:** The World's Leaders in Date Fruit Production [8]

Date seeds are about 10-15% of the date fruit weight which is known by its richness with different components such as valuable oil (5-13%). Date seeds are rich in dietary fiber, proteins, fatty acids, vital minerals, and other chemical compounds that, if extracted, might be used to make everything from cosmetics to food and medicine. The three parts of dietary fibers present in date seeds are cellulose (20–30%), hemicellulose (15-20%), and lignin (10-15%) Additionally, date seeds contain a wide range of fatty acids, such as oleic, linoleic, palmitic, lauric, myristic, stearic, and linolenic acids [9].

The cellulose is considered the basic structural component of date seed which is a linear polymer of glucose. Hemicellulose is a complex mixture of polysaccharides, including arabinoxylans that are frequently found mixed with cellulose and lignin. Lignin, a complex polymer, supports and rigidifies the seed structure.

The chemical structures of cellulose, hemicellulose, and lignin are illustrated in Figure 3 [9].



**Fig. 3:** Chemical Structure of Cellulose, Hemicellulose, and Lignin [9]

The aim of this work is to add value to date palm feedstock, a lignocellulosic agricultural waste by manufacturing bio-oil and bioethanol from date seeds through extracting oil from the date seeds using the most appropriate extraction procedures in order to boost the efficiency of the following stage in making bioethanol using biochemical conversion techniques. The study concentrates on efficacy of various pre-treatment techniques in order to build a sustainable, cost-effective, and environmentally friendly approach to bio-oil and bioethanol production. Therefore, the present study was aimed to investigate the efficiency of valorizing waste, generate renewable energy, and promote circular economy practices, particularly in middle east countries. We will discuss some previous studies and compare various products and their applications.

## 2 Feedstock characterization

In this section, the composition of date palm fruit, date seeds and the produced oil will be discussed.

Date palm (*Phoenix dactylifera* L.) seeds provide a promising source of bio-oil for biofuel generation. The date palm (*Phoenix dactylifera*) belongs to the genus *Phoenix* and is commonly grown for its edible fruit. Dates have been a part of the Middle Eastern diet for thousands of years that's used in different applications of cosmetic, health and industrial process.

Table 1 presents a comparison between date fruit and date seeds compositions.

Date seed oil is rich in fatty acids as follow: Oleic acid (40–55%), Lauric acid (10–20%), Linoleic acid (8–12%), Palmitic acid (10–15%) and Stearic acid (5–10%) [10].

The average weight of a palm seed is around 10–15% of the palm fruit weight [11]. The antioxidant content in palm date seed oil (DSO) was found to be comparable with olive oil, which can be a good source of antioxidant in order

to achieve the consumers' demand. Date seed oil is one of the major components of the date seed, which contain 5–13 % of oil [11].

To add value to our feedstock and make a zero-waste system, we will extract oil from the date seeds. Date seeds rich in lauric, oleic and other fatty acids which is valuable for cosmetics & pharmaceutical industries, soap & detergent production, biodiesel feedstock and animal feed supplement [12].

**Table 1:** Compositions of Date Fruit and Seeds [10].

Component	Date fruit	Date seeds
Carbohydrates	70-80%	65-75%
Sugars	55-70% (glucose, fructose, sucrose)	2-5%
Dietary fibre	6-11%	40-80% (cellulose, hemicellulose, lignin)
Protein	1.5-3%	2-6%
Fat	Lipids 0.1-0.5%	Oil 5-13%
Moisture	15-30%	4-10%
Ash	Minerals 1.2%	0.8-2.2%

### 3 Methods

In this section, the technologies of extracting both oil and bioethanol from date seeds will be explored.

#### 3.1 Methods for Bio-Oil extraction

Oil is extracted in different techniques that will be discussed as follows:

##### 3.1.1 Mechanical Extraction (Cold Pressing):

Cold pressing is more energy efficient and environmentally friendly than other techniques, making it preferable for processors. Oil is pressed without heating because heat can affect the oil's properties; the temperature should not exceed 50°C [13]. Stages of cold pressing are:

- 1- Seed cleaning and drying: we wash the oil seeds to insure we remove any dust on the surface and then dry to remove any moisture.
- 2- Seed crushing: important step to breakdown the structure to smaller particle size which increases the oil yield.
- 3- Oil collection: oil is extracted via cold pressing machine. Temperature is kept below 40°C and doesn't exceed 50°C. Oil is then collected in a vessel for sedimentation and finally purified with filters and stored in dark glass or stainless-steel containers to avoid oxidation.

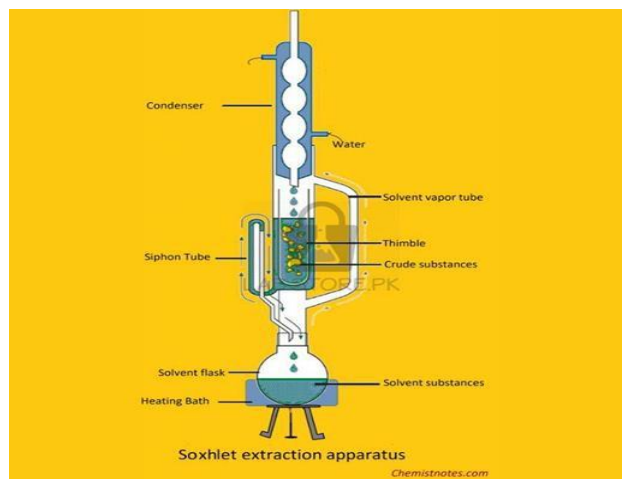
The remaining solid called “oil cake” or “pressed cake”, is used in enzymatic hydrolysis to produce bioethanol [14].

##### 3.1.2 Conventional Extraction (Soxhlet Apparatus):

A continuous solvent extraction method of oil from date seeds at ambient pressure and boiling temperature. It's commonly used in extracting bioactive compounds like lipids and fatty acids.

This method is based on the technique of recycling heated solvent which evaporates, condenses, passes through the solid sample and dissolves till we reach the volume then the system automatically siphons the loaded solvent to the

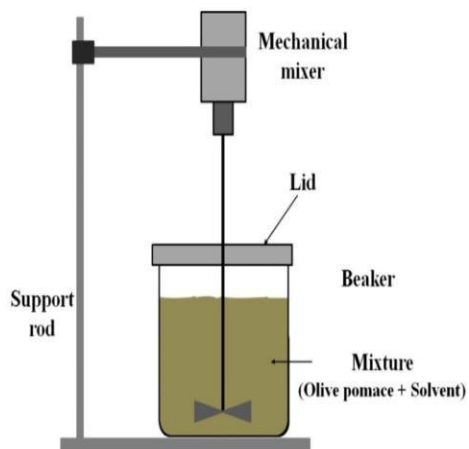
flask and the cycle repeats (4-8 hours). The solvent oil-mixture is evaporated to separate the oil. Figure 4 shows Soxhlet extraction apparatus [15].



**Fig. 4:** Soxhlet Extraction Apparatus [15]

**3.1.3 Soaking Extraction Method (Maceration):**

Soaking extraction is a simpler technique where the seed powder is soaked in solvent at room temperature for (24-72 hours) till the oil diffuses into the solvent. Figure 5 shows Soaking extraction apparatus [16].



**Fig. 5:** Soaking extraction apparatus [16]

**3.1.4 Comparison of bio-oil extraction methods:**

Soxhlet extraction is preferred over soaking and mechanical pressing as shown in the next Table 2 because it extracts more oil, works better with hard materials like date seeds, offers controllable heating temperature, and produces repeatable results.

**Table 2:** Comparison Between Extraction Techniques.

Feature	Cold pressing	Soxhlet extraction	Soaking extraction
Principle	Mechanical pressing (no heat or solvent)	Continuous solvent based extraction	Soaking the powder seeds in the solvent

Temperature	Doesn't exceed 50°C	Moderate to high (solvent boiling)	Room temperature
Solvent used	None	Hexane-ethanol...etc	Hexane- ethanol...etc
Oil yield	(3-5%)	(8-12%)	(5-8%)
Oil purity	Very high	Depends on solvent residue	Depends on solvent residue
Time required	Fast (minutes)	Long (4-8+hours)	Very long (24-72 hours)
Eco-friendliness	High	Low	Depends on solvent
Cost	Moderate (equipment)	High (equipment +solvent)	Low

Selecting a suitable solvent for extracting oil from date seeds depends on several properties that affect the oil yields including the following:

1. **Polarity:** Select a solvent with a polarity similar to the compound you want to extract to ensure it dissolves well.
2. **Boiling point:** The boiling point should be moderate, allowing for efficient evaporation and condensation cycles without degrading heat-sensitive compounds.
3. **Solubility:** The solvent should effectively dissolve the target compound while leaving other sample components behind.
4. **Volatility:** It's important to consider volatility, especially for less volatile compounds. Soxhlet extraction is not ideal for very volatile substances.

Table 3 shows common solvents used in oil extraction, properties, the common uses and the reason for selectivity.

**Table 3:** Common Solvents Used in oil Extraction [17].

Solvent	Boiling Point (°C)	Polarity	Common Uses	Why It's Used
Methanol	65	Polar protic	Plant metabolites, pigments	Strongly polar; good for polar compounds (though toxic).
Hexane	69	Nonpolar	Lipid and fat extraction, essential oils	Excellent for nonpolar compounds; low boiling point makes recovery easy.
Chloroform	61	Nonpolar	Lipid extraction, organic contaminants	Good solvency for nonpolar compounds but toxic and less environmentally friendly
Toluene	111	Nonpolar aromatic	Polymers, resins	Strong solvent for aromatic/nonpolar compounds; high boiling point for stubborn extractions.

From Table 3, hexane is generally the best solvent due to its high extraction efficiency, selectivity for nonpolar lipids, low boiling point ( $\approx 69^\circ\text{C}$ ), widely used industrially for edible oils, produces clear low acid oil and ease of recovery.

### 3.2 Methods for Bioethanol production

Bioethanol production from date seeds typically involves a sequence of steps: pre-treatment to enhance carbohydrate accessibility, hydrolysis to release fermentable sugars, and fermentation of sugars to ethanol, and finally, distillation and rectification to purify the bioethanol. The choice of specific methods for each step can vary depending on factors like cost-effectiveness, environmental impact, and desired ethanol yield [18].

### 3.2.1 Pre-treatment:

An essential stage in the process of producing bioethanol is pre-treating date seeds, sometimes referred to as date pits or stones. Due to the presence of lignocellulosic biomass in the date seeds, the date seeds have a complex structure that makes them naturally resistant to enzyme hydrolysis and microbial attack. Therefore, to optimize enzyme accessibility for fermentation, it is required to increase surface area and break down lignin and hemicellulose [19].

The date seeds contain 27.34% lignin, 20.63% cellulose and 13.49% hemicellulose [19]. Different pre-treatment techniques are used to obtain the final feedstock that will be used in the enzymatic hydrolysis step. These methods are classified into four types: physical, chemical, physicochemical and biological treatment depending on the type of biomass used [20].

#### 3.2.1.1 Physical pre-treatment

In order to break down the hard structure of lignocellulosic biomass, physical pre-treatment is an essential step. It improves hydrolysis efficiency and is frequently used in conjunction with other techniques to improve sugar and ethanol yields, even if it may not eliminate lignin.

##### 3.2.1.1.1. Mechanical treatment

To reduce the particle size of the date seeds and increase the surface area we use mechanical grinding and milling. The powder formed is then passed through sieve to separate the particles based on size. To remove the dust from the date powder we wash it with water and then we dry it by oven to remove moisture and then stored [20]. Mechanical pre-treatment increases the surface area of biomass, enhancing enzyme accessibility, but it often requires high energy input, making it less cost-efficient.

##### 3.2.1.1.2. Microwaves

This type of treatment depends on non-ionizing electromagnetic radiation to break down the lignocellulosic structure into agricultural by-products. A frequency between 300 MHz and 300 GHz (typically 2.45 GHz) is commonly used in industrial applications. Usually, it is carried out at a temperature ranging from 60–210 °C for 5–35 minutes [21]. This step enhances fermentable sugar yield for enzymatic hydrolysis. This method is fast and eco-friendly but expensive.

#### 3.2.1.2 Chemical pre-treatment

Chemical pre-treatment breaks down the complex structure of lignocellulosic biomass by using acids, alkalis, or other chemical agents. This process effectively breaks down lignin and hemicellulose, which promotes the hydrolysis's release of fermentable sugars. Because chemicals are used in chemical pre-treatment, some inhibitory by-products may be produced which necessitate careful handling, even though they greatly increase biomass digestibility and ethanol yield.

In acid hydrolysis method, diluted acids like hydrochloric acid (HCl) and sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) are frequently employed to break down hemicellulose and disturb the structure of lignin, increasing the biomass's accessibility for enzymatic hydrolysis. Nevertheless, this procedure may also result in the production of chemicals that limit microbial fermentation, such as 5-hydroxymethylfurfural (HMF), furfural, and acetic acid [22]. The typical operating conditions are acid concentrations between 1 and 5%, temperatures between 100 and 140 °C, and reaction periods between 30 and 60 minutes.

#### 3.2.1.3 Physio-chemical pre-treatments

Physical and chemical methods are merged to make the final biomass ready for the next process by increasing biomass surface area for enzyme action, decreasing cellulose crystallinity and fractionating lignin and hemicellulose [23].

##### 3.2.1.3.1 Ammonia fiber explosion (AFEX)

Liquid ammonia is used while exposing biomass to high temperature (60–100 °C) and pressure (1.72-2.09 MPa) to remove the lignin and keep a good amount of carbohydrates in short time [24].

### 3.2.1.3.2 Wet oxidation

Wet oxidation is a chemical pre-treatment method that creates reactive oxygen species that can degrade lignin and hemicellulose by combining oxygen or air and water at high temperatures and pressures. This increases cellulose's accessibility for enzymatic hydrolysis by solubilizing hemicellulose and partially oxidizing lignin. Reaction periods of 10 to 15 minutes, pressures between 0.5 and 2 MPa, and temperatures between 170 and 250 °C are typical operating conditions. Compared to other conventional chemical treatments, this approach has a lower environmental impact but is also more expensive and energy intensive [25].

### 3.2.1.4 Biological pre-treatment:

Microorganisms like fungi and bacteria were used to break down lignin and hemicellulose [26]. Common fungal species include brown rot, white rot, and soft rot fungi, while bacterial examples include *Paenibacillus campinasensis*, *Cellulomonas fimi*, and *Clostridium thermocellum* [27]. This method is considered low-cost and environmentally friendly, as it avoids the use of harsh chemicals and extreme conditions. However, a major limitation is the slow degradation rate, often requiring several weeks to achieve significant results.

### 3.2.2 Enzymatic Hydrolysis

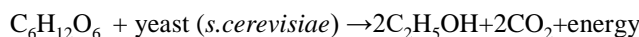
Enzymatic hydrolysis is defined as a process that uses specific enzymes to break down large molecules into smaller components by adding water to chemical bonds. It's the best choice because it needs less energy, has low toxicity and is low cost.

This technique breaks down complex molecules like carbohydrates, proteins and lipids to simpler compounds such as sugars, amino acids and fatty acids.

In this step we break down complex carbohydrates (cellulose and hemicelluloses) after previous pre-treatments into simple sugar glucose by using enzymes such as (amylase, cellulase) [28]. The typical conditions are ~50°C, pH 4.8–5.0, for 24–72 hours.

### 3.2.3 Fermentation

The resulting glucose from the hydrolysis step is fermented using microorganism on specific conditions to produce ethanol and carbon dioxide according to the following reaction [29]:



Key factors like temperature, pH, nutrient availability, and yeast strain significantly affect ethanol yield and productivity and need to be optimized. Optimal conditions typically include a temperature of 30–40 °C, pH around 4.5, and a fermentation time of 36–72 hours. Under these conditions, 90–95% of total soluble sugars (TSS) can be converted into ethanol and CO<sub>2</sub>, with ethanol concentrations reaching 10–14% by volume. Microorganisms used in fermentation vary depending on the sugar type, with *S. cerevisiae* being the most widely used due to its high productivity, low cost, and tolerance to ethanol. Other microbes include fungi such as *Candida shehatae* and bacteria like *Zymomonas mobilis* and *Escherichia coli*. [30,31].

### 3.2.4 Distillation and Rectification

The final step involves separating ethanol from the fermentation broth and purifying it to the desired concentration, typically through distillation—and rectification, to obtain fuel-grade bioethanol [32]. The aim of this step is maximizing ethanol recovery, purity and minimizing energy consumption.

Initially, the fermented mixture (containing 10–14% ethanol by volume) is pre-heated to 60–80 °C and introduced into the distillation system. In the first column, ethanol is distilled to approximately 75% by volume, and then further purified to 96% in a second distillation column [32].

This process exploits the difference in boiling points, with ethanol (boiling point 78.73 °C) evaporating first, then condensing and collecting in the reflux drum. Repeated distillation enhances the ethanol concentration to the desired level [33]. Industrial distillation systems are typically constructed from 304 stainless steel and may include up to 19

sieve trays to improve vapor–liquid contact and separation efficiency.

### 3.2.5 Process summary

Table 4 shows the sequence of producing bioethanol from date seeds, along with the purpose and conditions.

**Table 4:** Bioethanol production from date seeds [34-37].

Process	Purpose	Conditions/note
Cleaning-drying-grinding	Removes any impurities and increase the particle size that led to increase in oil yield.	Clean seeds →drying by microwave oven →grinded into fine particle size.
Oil extraction	Removes 5-13% oil to improve enzymatic hydrolysis and fermentation steps.	We will use Soxhlet device and our solvent is hexane.
Pre-treatments	We will break lignocellulosic structure to release cellulose and hemicellulose.	<b>Acid:</b> 0.5–2% H <sub>2</sub> SO <sub>4</sub> at 120–160°C. <b>Alkali:</b> 0.5–4% NaOH at 80–120°C.
Enzymatic hydrolysis	Convert cellulose and hemicellulose into fermentable sugar (glucose, xylose).	Enzymes: cellulase, hemicellulose. 45–50°C, pH 4.8, 24–72 hrs.
Fermentation	We will use microorganisms that convert simple sugar into bioethanol+ CO <sub>2</sub>	Yeast: <i>Saccharomyces cerevisiae</i> . Temperature (30–35°C), pH (4.5–5.5), time (24–72 hrs).
Distillation	Separates bioethanol from other fermentation by-products.	Produces ~95% ethanol. Additional dehydration for fuel ethanol.

## 4 Date Seeds Applications

### 4.1 Date Seed Powder:

Seeds are cleaned, dried, then ground into fine particle size. Could be used as a food ingredient that added to bread, biscuits, cereals ...etc and used as a caffeine base (free coffee alternative) [38].

### 4.2 Date Seed Oil:

By mechanical pressing or solvent extraction. Used in cosmetics & personal care: Moisturizers, Hair oils & conditioners, Anti-aging formulations (antioxidant-rich), Food industry: blended with cooking oil, pharmaceutical uses: wound-healing ointments [38].

### 4.3 Activated Carbon from Date Seeds:

Carbonization and activation (steam/chemical). Used in water purification and wastewater treatment [39].

### 4.4 Date Seed Biochar:

Used in soil modification [39].

### 4.5 Date Seed Animal Feed:

Grounded and mixed with other feed materials. Used as livestock feed (cattle, sheep...etc.) [40].

### 4.6 Date Seed Fertilizer:

Farming and soil improvement [40].

### 4.7 Date Seed Enzymes and Fermentation Products:

Bioethanol [40].

## 5 Previous Studies

This section explores the date seeds products and provides a comprehensive overview of current applications and future prospects of date seeds as an underutilized bioresource over the last five years.

### 5.1 Food industry products:

Seed flour from cultivar cv. Medjool: Total dietary fiber very high ( $\approx 67.9$ – $76.7$  g/100 g). Reducing particle size increased fat, minerals (Ca, Fe, Zn, Mg), and fatty acid contents; most abundant fatty acid was oleic acid. Polyphenols (catechin, epicatechin, epigallocatechin-3-gallate) were dominant, and antioxidant capacity (ABTS, DPPH, FRAP) improved with finer milling [41].

Cookies: A 2021 study substituted part of wheat flour with date-seed powder — 12% substitution was found “highly acceptable” by sensory panel, yielding cookies with elevated fiber and altered macronutrient profile (e.g. higher fat, lower carbs) compared to pure wheat cookies [42].

Bakery & dairy analogues: Recent reviews/industrial-application studies propose using date-seed fiber/oil as fat replacers, dietary fiber enhancers, and natural antioxidants in products like cheese, yogurt, spreads, baked goods — though texture and sensory trade-offs noted, especially at higher substitution levels [43].

Meat products: A 2024 Egyptian study used date seed powder to improve oxidative stability of beef and chicken burgers, demonstrating strong DPPH-scavenging activity (81.4%), low  $IC_{50}$  (0.59 mg/mL), and measurable phenolic, flavonoid, saponin, anthocyanin content, suggesting date-seed powder can act as a natural antioxidant for extending shelf life [44].

Date seed coffee: this study determined producing a caffeine free from roasted date seeds powder and we tasted (10–50% substitute with coffee), the first method scored an exchange grade that made it suitable for caffeine sensitive consumers than blending 50/50 [45].

### 5.2 Cosmetic and pharmaceutical applications:

Cosmetic creams and oils: date seeds oil can be used in formulas of creams, moisturizers, shampoos, serums and other skincare products for its richness in antioxidant, anti-inflammatory, and UV-protective properties [46].

Medical supplements: Studied extracts’ anti-inflammatory, antibacterial, and anti-diabetic properties [47].

### 5.3 Engineering and environmental uses:

Bioethanol: Date-palm seeds (three types) may be fermented with *Saccharomyces cerevisiae* after being pre-treated (acid hydrolysis) to remove the cellulosic/hemicellulose fraction. After six hours of fermentation, up to 21.57 g/L of ethanol was produced, proving that date-seed-derived bioethanol is feasible [48].

Bio-oil: Date seeds contain 5–13% oil, which contains essential components such as lauric and oleic acids, tocopherols, phytosterols, and phenolic compounds, making them a prospective source for a variety of food, cosmetic, and pharmaceutical applications [49].

Activated carbon: used for water treatment, microcrystalline cellulose for pharmaceuticals and composites [50].

### 5.4 Animal Feed & Aquaculture:

Date seed used as a feed ingredient for livestock and aquatic animals [51]

## 6 Conclusion and Opportunities

Transforming waste into wealth is the key model in this research that contributes to different applications including food, energy, and medicine. Future efforts should prioritize:

- Optimizing extraction techniques for improving yield and cost efficiency.
- Focusing on integrating date seed value into sustainability frameworks.
- Evaluating the environmental impact of date seed products and promote their adoption in industry.

The sustainable utilization of date seeds is an example of agro-waste valorization, enhancing innovation and eco-friendly practices across multiple fields.

For the Egyptian date seeds the most efficient technology is Integrated Biorefinery Approach:

[solvent extraction (bio-oil) → pre-treatment of defatted seed cake (alkali treatment) → enzymatic hydrolysis (fermentable sugars) → fermentation (bioethanol)] due to the following: Egyptian date seeds contain 10-15% oil and high cellulosic structure and improving the fermentation efficiency by extracting oil in the first step.

Despite these advantages, challenges remain that should be solved including variation of date seeds composition, not economical for small scale processing, enzymes high cost and energy intensive processing.

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