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Review

Date Palm Tree Waste Recycling: Treatment and Processing for Potential Engineering Applications

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Abstract: Date palm, the most important tree in Saudi Arabia and the Middle East, produces a huge amount of waste yearly in the form of fibrous materials, dried fruits, and seeds. Such waste is a great source of excellent degradable biomass that can be used in numerous applications as natural fiber composites, active carbon precursors, and even nano-featured sheets. That rich resource is yearly burned on date palm farms due to the lack of effective processing strategies. This review offers a scientific evaluation for date palm waste in terms of specifications and applications, and it proposes pre-treatment processes to produce fibrous and powder raw materials to be used in some engineering and industrial applications. Additionally, some possible advanced industrial applications, such as active carbon and natural fiber composites, will be discussed and reviewed.

Keywords: date palm; waste; recycling; natural fiber composites; NFC; active carbon precursor; palm waste; palm residue; waste management

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1. Introduction

Palm trees are a type of evergreen plant belonging to the Arecaceae family. Figure 1 shows a schematic figure of a date palm tree. Palms are recognized by their fan-shaped or feather-like fronds (leaves) and fiber-covered trunks or stems. There are over 2600 species of palm trees that are grouped into over 200 genera. The most widespread palm in the Middle East is the palm tree due to the suitable climate for date palm and its delicious fruit full of nutrition [1]. The famous date palm is considered a renewable natural resource because it can be replaced in a relatively short period of time. It takes around six years for date palms to bear fruit after planting and around nine years to produce viable yields for commercial harvest. Usually, date palm wastes are burned on farms or disposed in landfills, which cause environmental pollution in date-producing nations. A wide range of physio-chemical, thermal, and biochemical technologies exist for sustainable utilization of date palm biomass. In addition, date palm has a high volatile solid content and low moisture content. These factors make date palm residues an excellent biomass resource in date-palm producing nations [2]. Figure 1 shows a schematic for the date palm tree where the different components and sources of waste can be observed. Figure 2 shows a real picture for the date palm tree.

The average economic life of a date garden is 40 to 50 years, but some are still productive up to 150 years [3]. During this life span, date palm requires special care. The offshoot should be removed, and dead or defective fronds need to be removed yearly, which generates about 20 kg of waste per year from only one date palm. Some studies have reported that Saudi Arabia alone generates more than 200,000 tons of date palm biomass each year [2].

The date palm wastes are in the form of fronds, offshoots, dried fronds base (karab), and date pits. According to local farmers, they usually collect this waste and burn it. A small fraction of the waste is shredded and blended with other bio waste to be used as animal feed, or leaved aside to break down naturally to be used as fertilizer. This article's main purpose is to prove that date palm waste processing research is worth investing in.

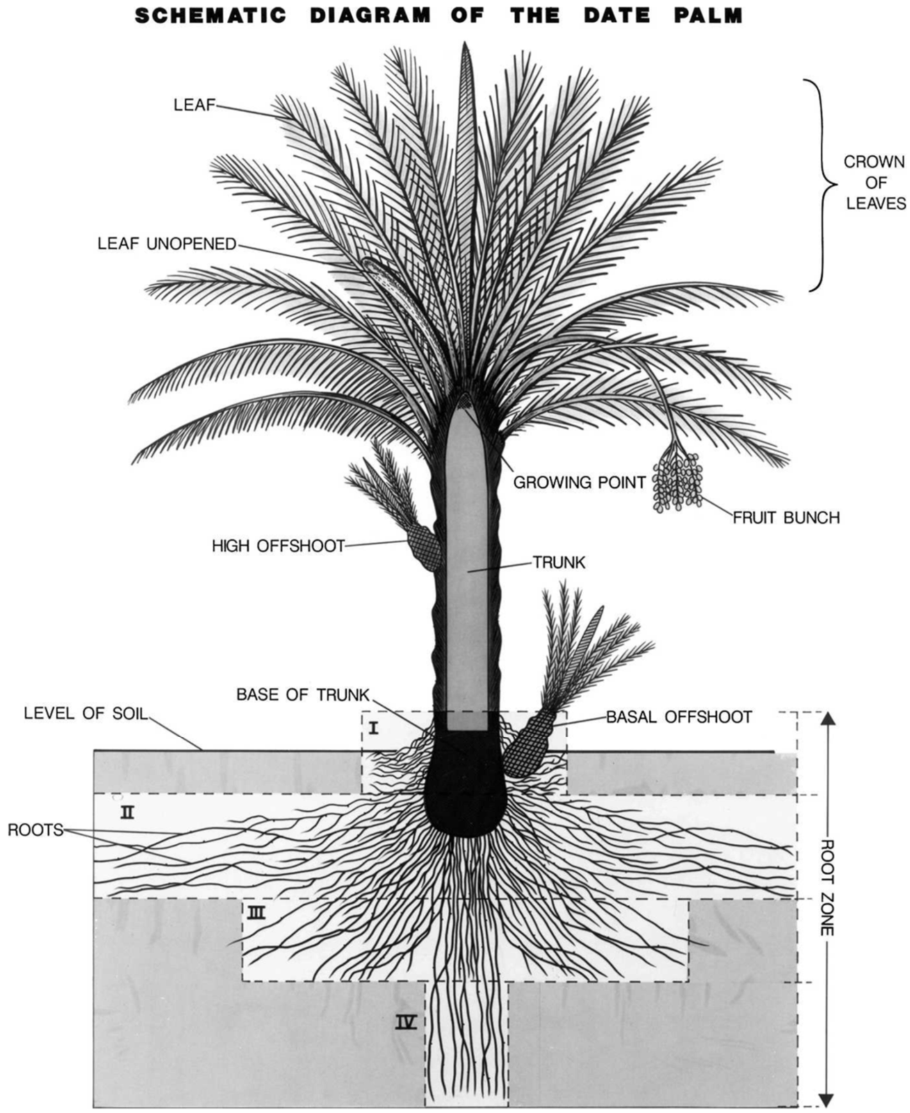

Figure 1. Date palm tree schematic [3].

Figure 2. Real picture of a date palm tree.

2. Date Palm Waste Properties

Industrial utilization of date palm waste requires detailed study of the mechanical and chemical properties in addition to specified study of mechanical properties, nutrition, or pyrolysis analysis, depending on the required application. However, date palm waste is generated from several parts of the date palm tree. Date palm trees generate waste yearly in the form of frond, empty fruit bunch, date palm fiber, and dried fruit, while waste as empty trunks is generated from dead palm trees; date palm seeds (called date stones or pits) on the other hand generate waste from date paste industries. Figure 3 shows a picture of the date palm tree frond (leaf), as each part has different compositions and properties.

Figure 3. A picture of date palm frond (leaf).

2.1. Fruit Waste Nutrition

Due to the high nutrition of the date fruit, its waste is used as animal feed or even as fertilizer. However, Lattieff suggested using it as a biogas precursor [4]. As date fruit is not suitable to be used in mechanical structures, the chemical composition and nutrition of date fruits only was reviewed. Table 1 gives the approximate nutrition of 10 fresh and 16 dried varieties of date fruit.

Table 1. Approximate nutrition analysis of 10 fresh and 16 dried varieties of date fruit [5,6].

	Fresh Dates		Dried Dates Range	
	Range	**Average**	**Range**	**Average**
Moisture (g/100 g)	37.9–50.4	42.4	7.2–29.5	15.2
Protein (g/100 g)	1.1–2.0	1.5	1.5–3.0	2.14
Fat (g/100 g)	0.1–0.2	0.14	0.1–0.5	0.38
Ash (g/100 g)	1.0–1.4	1.16	1.3–1.9	1.67
Carbohydrates (g/100 g)	47.8–58.8	54.9	66.1–88.6	80.6
Total sugars (g/100 g)	38.8–50.2	43.4	44.4–79.8	64.1
Fructose (g/100 g)	13.6–24.1	19.4	14.1–36.8	29.4
Glucose (g/100 g)	17.6–26.1	22.8	17.6–41.4	30.4
Energy (kcal/100 g)	185–229	213	258–344	314

2.2. Date Palm Waste Chemical Composition

Date palm waste is mainly fibrous, which is why chemical studies focus on the fiber. The importance of this area of study appears in the relation between chemical composition and some important natural fiber characteristics such as degradability, recyclability, weather resistance, fungi attack, etc. Those characteristics strongly depend on the chemical composition [7]. Figure 4 shows the natural fiber structure, while Table 2 contains the chemical composition of date palm fronds and its average weight percentage.

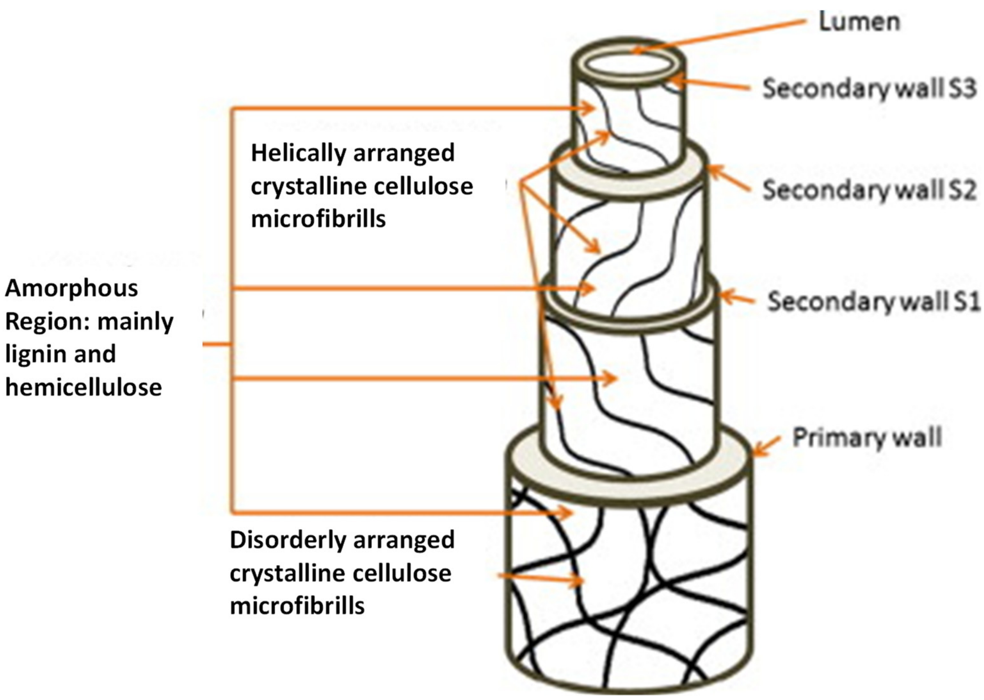

Figure 4. Natural fiber structure [8]. (Copy right permission from Elsevier).

Table 2. The average weight percentage of chemical components of the date palm leaf [9] and its leaflet and rachis parts [10].

Constituents	Cellulose	Hemicelluloses	Lignin	Ash	Extractive
Leaf	54.75%	20%	15.30%	1.75%	8.2%
Leaflet	40.21%	12.8%	32.2%	10.54%	4.25%
Rachis	38.26%	28.17%	22.53%	5.96%	5.08%

Plant fibers consist mainly of cellulose fibers embedded in a lignin matrix. What makes palm fiber special is the bio-structure that gives it good mechanical properties. The structure starts with a primary wall surrounding three secondary walls. Each wall is formed of hemicelluloses, and lignin acts as a matrix, while the cellulose molecules chain up as a series of helically wound cellular micro-fibers on each wall exterior [7]. It is noticeable that the palm fiber is hollow due to the lumen presence, unlike synthetic ones.

2.3. Physical Properties of Date Palm Waste

For industrial usage, the study of physical properties is important for engineers to effectively apply natural fibers in engineering products and applications. The key physical properties of natural fibers that scientists and researchers study are fiber length, diameter, density, thermal conductivity, cost, and availability [11]. Table 3 shows the range of physical properties.

Table 3. Physical properties of date palm fiber [11].

Density (g/cm^3)	0.9–1.2
Length (mm)	20–250
Diameter (µm)	100–1000
Specific modulus (approx.)	7
Elongation to break (%)	2–19
Thermal conductivity (W/m K)	0.083

2.4. Thermal and Pyrolysis Characteristics

Each date palm tree yields approximately 40 kg of burnable waste annually [12], making date palm waste a good energy source in the Gulf region. To utilize such wealth, the study of thermo-chemical characteristics, including combustion and pyrolysis of date palm waste, is important. This is key information to design pretreatment processes or to use date palm waste as bioenergy or bio-chemical sources. Those characteristics have been studied by Hussain et al. [13] and Sait et al. [14]. They used thermogravimetric analyses to investigate the combustion, pyrolysis behavior, kinetics of pyrolysis, and combustion of date palm biomass including seeds, leaves, and stems [13,14]. Their data are available in Tables 4 and 5.

Table 4. Approximate analysis of date palm biomass [13]. Values assigned with 1 from Sait et al. [14].

Biomass	Moisture	Volatile Matter	Ash	Fixed Carbon	Lower Heating Value (LHV) (MJ/kg)
Seed	5.1%	75.1%	9.8%	8.1%	-
Leaf	5.3%	77.5%	12.1%	6.1%	-
Leaflet	5% [1]	78% [1]	11.7% [1]	5.2% [1]	17.9 [1]
Rachis	17.7% [1]	55.3% [1]	19.2% [1]	7.8% [1]	10.9 [1]
Stem	18.1%	52.1%	20.2%	8.1%	-

Table 5. Ultimate analysis of date palm biomass (wt %) [13].

Biomass	Carbon	Hydrogen	Nitrogen	Sulphur	Oxygen
Seed	44.1%	6.1%	0.9%	0.6%	48.3%
Leaf	50.4%	6.3%	1.1%	0.4%	41.8%
Stem	38.1%	5.2%	0.8%	0.3%	55.6%

2.5. Mechanical Properties of Date Palm Fiber

The mechanical properties of natural fibers are strongly affected by several variables such as structure, microfibrillar angle, chemical composition, cell dimensions, and defects. According to Al-Oqla et al. [11], microfibrillar angle is the angle between the fiber axis and the micro-fibrils. These angles are responsible for the mechanical properties of the fibers. The smaller the angle, the higher the strength and stiffness of the fiber; larger angles usually provide higher ductility [11]. Generally, natural fibers with higher mechanical strength possess higher cellulose content, longer cell length, higher degree of polymerization of cellulose, and lower microfibrillar angle. Important mechanical properties, such as tensile strength and Young's modulus, usually increase as cellulose content and cell length increase [7]. Table 6 shows the mechanical properties of date palm fiber.

Table 6. Tensile strength and Young's modulus of date palm fiber [7].

Tensile strength (Mpa)	58–203
Young's modulus (Gpa)	2–7.5

2.6. Characterization of Date Palm Fibers for Mechanical Applications

Date palm fiber waste is valuable waste due to the huge diversity of its applications. Since date palm fibers are natural fibers, the physical, chemical, and mechanical properties are impossible to control and vary a lot in the harvesting stage due to many natural variables such as soil, the tree condition, climate condition, diseases etc. Moreover, the fiber extraction process can also affect its properties. The properties stated before are approximated in wide ranges of the raw date palm fibers. That is why characterization criteria and property control methods are required for industries to benefit from date palm fiber in engineering applications. As the control method will be discussed in a separate section, characterization criteria based on Al-Oqla et al. [11] will be suggested here. They developed a criterion to prove the feasibility of date palm fiber for automotive industries. However, by modifying their criterion, one can characterize the date palm fiber, design a proper pretreatment plan, and choose the required date palm fiber type and specification for specific applications. Figure 5 shows a section schematic of natural fiber.

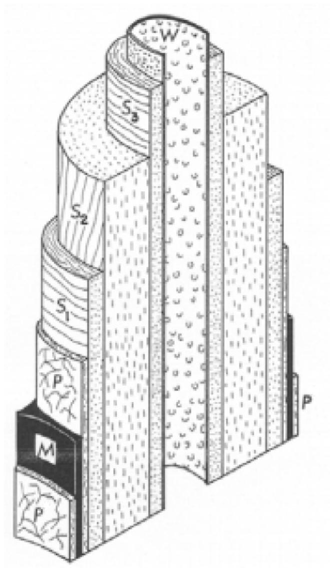

Figure 5. Section view of the plant fiber. M is the middle lamella connecting the fibers in the plant; P is the primary layer; S1, S2, and S3 are the three secondary layers; and W is the cell membrane [15].

(1) Cellulose and lignin content

Cellulose, hemicellulose, and lignin are the main components of the cell wall of natural fibers. However, the percentage of each of them greatly affects the natural fiber mechanical properties and wettability. Date palm fibers have a good balance of cellulose, hemicellulose, and lignin, providing good wettability resistance and preferable mechanical properties compared to other natural fibers. Furthermore, date palm waste offers a good diversity of fiber with different cellulose and lignin contents depending on which part of the tree the fiber is extracted from.

(2) Density

One property for which natural fiber is superior to synthetic is the low density, due to the hollow cylindrical fiber structure of natural fiber, as seen in Figure 5. That low density comes with very good mechanical properties, even if it is lower than synthetic fiber, but on the other hand it provides higher specific properties (mechanical properties related to fiber weight or density) such as specific tensile strength and specific modulus of elasticity [11].

(3) Fiber aspect ratio

Length-to-diameter ratio (L/D) or the fiber aspect ratio is critical in the fiber selection. Continuous fibers have a high aspect ratio and lead to a generally stronger and stiffer composite, while discontinuous fibers have a low aspect ratio, which is suitable for complex parts and large-scale production. The raw date palm fiber aspect ratio (L/D) is 200–250, and continuous fibers can be easily cut to provide discontinuous fibers. This makes it suitable for a huge range of applications depending on the processing procedure.

(4) Thermal conductivity

Due to the hollow fiber structure, natural fibers ensure very low thermal conductivity compared to synthetic fibers. Date palm fibers, especially with their thermal conductivity of 0.083 (W/m.K), are a great choice for insulation [11]. Date palm fibers are great reinforcements for composites used in buildings such as wooden cement and Gibson boards.

(5) Availability

Dates are one of the most important fruits in the Middle East. According to Zafar, date palm waste in Saudi Arabia alone is estimated at 200,000 tons yearly, making date palm fiber one of the most available natural fibers [2]. However, availability may change depending on geographical location. Palm waste is highly availability not only in the Middle East but also in other regions since coconut and oil palm waste inhibit similar specifications to date palm waste.

(6) Raw fiber cost

Because date palm fiber waste is difficult for farmers to get rid of, the cost of the raw fiber is low. According to Al-Oqla et al. [11], date palm fiber cost is estimated at 0.02 $/Kg [12]. Such cost may also be different depending on many factors.

3. Date Palm Waste Pretreatment

Date palm waste is a natural raw material with great potential. However, natural raw materials have considerable property variations due to many factors such as tree condition, harvesting conditions, etc. For industrial production, especially mechanical industries, well-defined properties of the raw material are mandatory. Synthetic raw material properties are well defined, unlike natural materials, due the controllability of the production factors. Such control is not applicable for natural material, especially with date palm waste, due to the fact that it is a waste recycling, and the main product of date palm is the date. Date palm waste properties can be controlled by pretreatment processes. Defining and modifying the properties and even adding favorable properties or removing unfavorable ones is possible.

3.1. Physical and Chemical Treatment

Physical treatment of date palm fiber involves controlling the following: length [16], aspect ratio [16], water content [17], ash (inorganic chemical residues containing Ca and K), volatile content, extractive content [17], and surface bonding [7]. Most of these properties are controlled by cutting or shredding, grinding, and heating. Other physical treatments, such as surface fibrillation and electric discharge, are used to control surface bonding [7].

Chemical treatment of date palm fiber controls the following: ash and extractive content [18], surface bonding [7,19], and cellulose, hemicelluloses, or lignin content [19].

However, chemical treatment is basically used to control ash, extractive content, and surface bonding by washing or soaking in water or organic chemicals. Table 7 lists the physical and chemical treatments used by researchers in the reviewed articles.

Table 7. Chemical and physical treatments applied by researchers on natural fibers.

Treatment	Processes Applied	References
Physical	Sizing: Cutting, Shredding, Grinding	[16,20–22]
	Drying	[23]
	Surface Fibrillation	[7]
	Electric Discharge	[7]
	Steam Treatment	[7]
Chemical	Sodium hydroxide (NaOH) treatment	[7]
	Acetylation	[7]
	Graft Copolymerization	[7]
	Permanganate Treatment	[7]
	Silane Treatment	[19]
	Benzoylation Treatment	[24]
	Acrylation and Acrylonitrile Grafting	[24]
	Maleated Coupling Gents	[25]
	Peroxide Treatment	[25]

3.2. Pretreatment Methods

Pretreatment can be planed based on the required raw material (fiber or powder) and the final product (composite, active carbon, biochar, etc.). The same division of date palm waste used in the properties study can be applied in the pretreatment methods. So, the date palm waste pretreatment will be divided into fiber pretreatment and powder pretreatment.

The first step in the pretreatment of either fiber or powder is by sorting the waste into the following: a—leaflet, b—rachis, c—seed (fruit stone), and d—fruit bunch.

3.2.1. Fiber Pretreatment

Date palm fiber is available in the leaf (frond), trunk, and the mesh fiber surrounding the trunk. The main source is the leaf and the fruit bunch, which are removed from the tree yearly as waste. The frond consists of the leaflet and rachis, as shown in Figure 3. Each part's fibers have different properties, and each were detailed in Section 2. The suggested fiber pretreatment steps are the following:

(1) Fiber extraction

Most researchers who studied the date palm fibers shredded or cut the fibers before any chemical or physical treatment [16,20,26,27]. Such a process limits the length of the fiber to a few centimeters and, therefore, the aspect ratio decreases the overall mechanical properties. Furthermore, processes such as shredding result in undefined fiber length and diameter, making it not favorable for engineering applications, especially in composites where the reinforcement length and diameter strongly affect the composite properties. To get the full length of the date palm fiber, and controllable length and diameter, a fiber extraction process should be used. Natural fiber extraction processes are classified into the following [28]:

(a) Biological extraction

Biological extraction is done by a retting process. Such a process uses bacteria to break the bonds between fibers. Retting can be classified to water retting and dew retting. Such a process requires a long time and can exceed twenty days. In addition, it affects the mechanical and chemical properties of the fiber. However, biological extraction is the most economical extraction method.

(b) Chemical extraction

Chemical extraction is done by soaking the fiber source in an organic chemical substance such as NaOH. The concentration, duration, and temperature depend on the fiber source and the desired properties, as such an extraction process significantly affects the fiber properties. Alawar et al. studied the effect of sodium hydroxide and hydrochloric acid treatment at various concentrations on the date palm fibers [29].

(c) Mechanical extraction

Mechanical extraction is the fastest extraction method, using a mechanism called a decorticator. Such a machine is used to extract natural fibers [30]. Unfortunately, research studying the effect of mechanical extraction on date palm fibers was not found. Decorticators are a favorable extraction mechanism due to the speed of the extraction process and the lack of chemicals or bacteria that affect the properties of the fiber. This allows for faster, easier, and more efficient chemical or physical treatment.

(2) Washing

Date palm fiber sources include the waste leaf, bunch, or trunk. Such waste is exposed to soil and weather conditions, and cleaning is required to get the highest fiber quality. Hegazy et al. [20] studied the effect of washing on the date palm fiber mechanical properties and its effect on the reinforced composite properties [20]. Washing can be done by water or chemicals to remove the ash and some extracts.

(3) Surface and wettability modification

Date palm fibers are mostly used as composites reinforcement. For such application, the wettability of the fiber should be decreased while increasing the adhesion with a matrix that is usually a polymer. Such modifications can be done by chemical or physical treatments, mentioned in Table 7.

(4) Drying

Drying is an important pretreatment step to reduce the water content and remove the extractive, which decreases the weight of the fiber and decreases the density. Drying can be done by the sun (or in the open air) [29,31] or oven [16,20]. Even though drying by the sun is the more economical method, the oven is suggested due to the controllability and speed.

3.2.2. Powder Pretreatment

Many applications of date palm waste require the raw material to be powder, as active carbon, biochar, and water desalination. Unlike the fibers, any part of the waste can be processed to powder. However, converting the palm waste to powder requires it to be dried to the minimum level of water content. Powder pretreatment is easier than fiber; it is more controllable and has been studied enough by many researchers [18,32–34]. While taking some of these studies into account, the powder pretreatment procedure will be as follows:

(1) Shredding

This step is needed if the date palm waste is from the leaf or trunk. Due to the size of such parts, the cleaning process is not efficient. Shredding also makes the drying process faster, less power consuming, and more efficient, as the surface area of the raw material is much larger. Shredding is not necessary for the seeds.

(2) Washing

Cleaning of the shredded waste is very important in the powder production process as any additive other than the raw date palm material will affect the powder even more than the fiber production due to the small size of the powder. Washing of date palm waste for powder production usually consists of chemicals, as they remove ash particles that are chemically bounded to the powder, and washing with chemicals helps in removing moisture, ash, volatile matter, and extracts from the date palm waste [18].

(3) Drying

Drying of date palm waste for powder production strongly affects the next step, grinding, as grinding wet material will result in dough instead of powder. That is why drying of the date palm is needed, to remove any extracts or water content. Such a drying process cannot be done by sun or open-air drying; it requires a controlled oven in dry climate.

(4) Crushing/Grinding

Crushing of dried material is an easy process. It can be done by almost any grinding mechanism. However, not all grinding mechanisms offer the full controllability of the final size. To control the size, a Cross Beater Mill is suggested. For nano sized powder, mechanical ball milling is preferred.

(5) Sieving

For accurate powder size control, sieving is important, especially if the grinding mechanism did not offer enough control. Researchers have used that method for such cases [35,36].

4. Potential Applications of Date Palm Waste

Waste management was not a priority concern for scientists and engineers for decades. Waste in many industrial and agricultural fields was simply burned or disposed to the land or water with little or no treatment. However, the global warming problem and huge amounts of waste made such options not only harmful to our environment but also to our economy in the long term. The palm industry, including oil palm and date palm industries, still lack effective waste management. Several studies on the applications and products of palm waste were published recently, but the proper industrial usage of such application is still limited. Four manufacturing applications of date palm waste will be discussed in this section from the perspective of engineers, to produce manufacture engineering products, along with discussion of the required treatments, specifications, manufacturing methods, and the final product specifications.

4.1. Composites from Date Palm Fibers

Natural fiber composites (NFC) are composite materials that are mostly polymer based and use natural fiber (or might be called vegetable fiber) as reinforcement (filler). Such fibers have been extracted from sisal, coir, jute, ramie, pineapple leaf (PALF), kenaf, and other natural sources. However, researchers recently started studying the ability to use biomass waste as source of natural fiber. Wastes such as rice husks, wheat-cereal straw, tobacco, sunflower stalks, bagasse, oil palm, bamboo, cotton carpel, and date palm fibers have been mention in the Mehdi et al. review [37]. Natural fiber has attracted a lot of attention lately due to its superior advantages over conventional reinforcement materials such as fiber glass. Natural fibers are considerably low-cost and are more available compared to conventional fibers with low density; they have good mechanical properties [38] and very good thermal and acoustic insulation. Natural fibers are also biodegradable and nonabrasive. Unfortunately, natural fibers have adhesion problems with hydrophobic polymer matrix [38], wide variation in mechanical properties [38], poor moisture resistance [38], low degradation temperatures [39], and processing complexity, which are major problems facing the employment of natural fibers in industrial investments. Researchers in the Middle East, mostly in the Gulf countries, focused their investigation on date palm fibers due to the large number of date palm trees, making its fiber one of the most available natural fibers and the most important one in the Middle East.

To prove the ability of date palm fibers as a great reinforcement, numerous studies on date palm NFC have been reviewed. The following products have been prepared and tested using laboratory equipment, making industrial-level production a problem of time.

(1) Polypropylene composites

Haque et al. investigated the mechanical properties of palm fiber as reinforcement for a thermoplastic polymer polypropylene matrix. They used full-length fibers treated chemically with benzene diazonium salt to improve surface adhesion with the matrix. For comparison, untreated raw fibers were used. The result showed a dramatic decrease in tensile strength but, on the other hand, great improvement in the flexural strength and impact strength up to 30%wt fiber. Additional fiber weight in the matrix had no effect in all their tests. Chemical treatment of date palm fibers greatly improved the mechanical properties, compared to untreated fibers, due to the better adhesion with the matrix and the lower wettability [31].

(2) Epoxy composites

Saba et al. investigated the mechanical properties of date palm fiber in an epoxy matrix. They grinded the fiber into 0.8–1 mm powder using a laboratory grinding machine after cleaning and drying the fiber in the oven. The use of date palm fiber as reinforcement greatly enhanced the tensile and impact strength in addition to the plasticity of the composite. They found that the optimum weight percentage for the reinforcement was 50%wt; however, their SEM images (shown in Figure 6) of the tensile fracture showed the presence of air bubbles in the epoxy matrix, which affects the mechanical properties, unlike the pure epoxy resin where air bubbles were not present [40]. Finding a better manufacturing process for such a composite is suggested to obtain better mechanical properties.

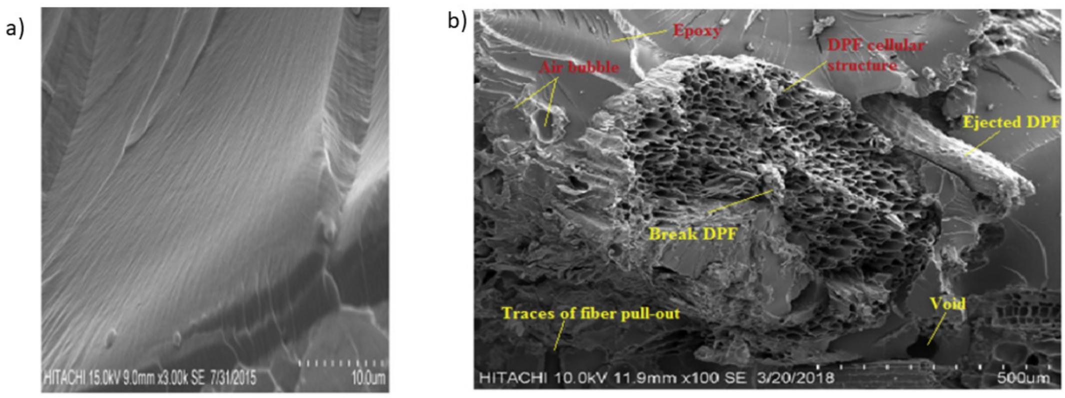

Figure 6. SEM images of tensile fractures from (**a**) pure epoxy resin and (**b**) sample of 40% DPF/epoxy composites [40].

(3) Oriented strand board from date palm

Hegazy et al. [20] successfully manufactured oriented strand board (OSB), one of the most used engineering wood-based panels; they used date palm fronds collected from Al-Kharj. They made OSB with good mechanical properties and dimensional stability. However, better results could be obtained by improving the adhesion and compression processes [20]. Such application has great economical potential due to the processing and manufacturing simplicity and the high demand for OSB.

(4) Medium-Density Fiberboard (MDF)

Hosseinkhani et al. [41] successfully manufactured MDF board using date palm fronds that have great mechanical properties. To test the factors that affect the MDF quality, they manufactured the MDF board using 2 resin types, 3 pressing levels, and 10 and 12 %wt resin (total of 15 specimens). They proved that the MDF made of date palm fronds had mechanical properties and wettability resistance that exceeded the requirements of EN standard for MDF [41].

(5) Particle board from date palm

Hegazy et al. [16] in Saudi Arabia, and Amirou et al. [26] in Algeria, studied the feasibility of using date palm trunk and rachis as raw materials for particleboard manufacturing. Amirou et al. proved that both of them are superior materials for such applications compared to EN standards for particleboard [26]. Hegazy et al. [16] used date palm rachis to study the effect of various factors in particleboard manufacturing, such as date palm cultivar, particle size, hot water extraction, and panel density, on the mechanical properties of the particleboard [16]. Ferrández-García et al. also used palm rachis to manufacture low-cost particleboard, but they compared between different sources of rachis which were date, canary, and Washingtonian palm [42]. Researchers who studied the manufacturing of particleboard using date palm waste have reached various results, and the right choice of the manufacturing parameters depends on the intended application of the particleboard and the standards assigned to that application.

(6) Gypsum board reinforcement

Gypsum board is usually used as a thermal or acoustic insulator because gypsum board has good insulation. Aymen et al. [43] studied the thermophysical effect of reinforcing gypsum board with date palm fibers. They proved that date palm fiber reinforcement greatly decreased the thermal conductivity and the density of the gypsum board, leading to better insulation with less weight [43]. Such improvement happened without sacrificing the mechanical properties. In a real-world setting, according to Al-Rifaie et al. [44], date palm fiber reinforcement improved the mechanical properties and modified the fracture mode of the gypsum plaster from brittle type to quasi-plastic type [44].

4.2. Biochar

Biochar is charcoal produced by biomass pyrolysis, which is so far used as a soil conditioner for sequestering carbon and soil health benefits in the absence of oxygen. Converting plant biomass into biochar that can be combined with the soil is a viable approach for making plant nutrients accessible to the soil and improving soil structure. Biochar is a slow or rapid biomass pyrolysis commodity, although higher biochar yields for slow biomass pyrolysis are also recorded. Approximately 20–80 t ha^{-1} of carbon (C) was lost, resulting in reduced soil and water quality and production of biomass. Soil C compounds (organic compounds that store carbon) are essential to enhance soil fertility and productivity. A viable alternative for lowering ambient carbon dioxide and growing soil carbon dioxide is the production and usage of biochar in the soil [45]. Biochar's ability for climate change mitigation is due to its highly reactive nature, which slows down the pace at which biomass photo-stable carbon is transported to the atmosphere [45]. In addition to improving soil carbon accumulation, biochar-related advantages include improving soil quality and efficiency, decreasing nitrogen losses, increasing soil water holding capacity, immobilizing heavy metals, and being cost-effective [45].

Converting Date Palm Waste into Biochar

Palm waste pyrolysis is cost-effective and eco-friendly, and using concentrated solar thermal energy is the process. The process is shown in Figure 7. Waste collecting and cleaning, drying, volume decreasing, charging into the solar heating unit, and storage are part of the process [17]. Dust and ash-forming elements or inorganic mineral content of biomass are reduced by washing the bulk flow biomass with water. The washed biomass is dried with hot air in a rotary dryer for 6 h. The dried biomass is shredded and milled, as the particle size of the biomass is fed into a pyrolysis unit and influences the consistency of the commodity. The milled dry particles are then transported to the concentrated solar energy pyrolysis device by a belt conveyor to the receiver or stirred reactor. The solar pyrolysis machine can be filled manually or managed in batch mode, depending on process size and scale. To improve biochar, Ahmad et al. [45] studied the effect of impregnating biomass with silica or zeolite using a method described by Yao et al. [46], and they successfully improved the biochar stability.

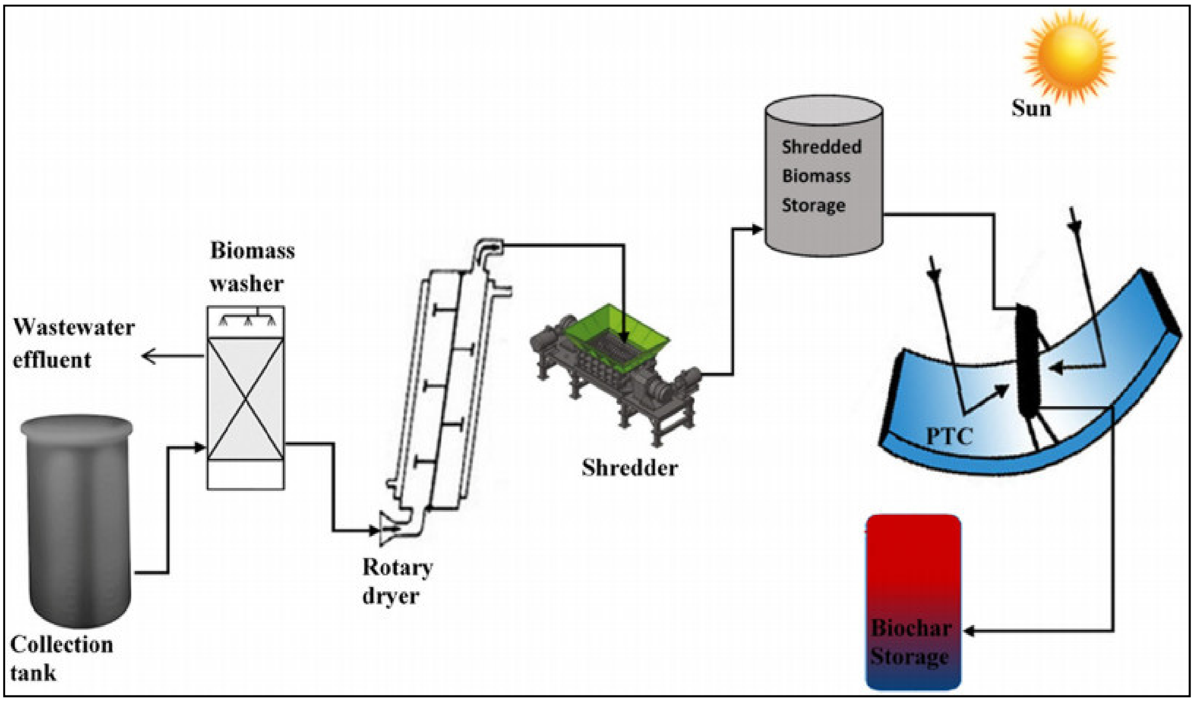

Figure 7. The process of converting date palm waste into biochar [17]. (Copy right permission from Elsevier).

4.3. Active Carbon

Activated carbon, also known as activated char or solid sponge, is an amorphous, non-graphite, carbonaceous compound and is a product of activating carbonaceous material with a carbon content of 72–90% [21]. Active carbon can be manufactured by various precursors with no specific chemical composition or formula. However, active carbon can be defined as "a material prepared to exhibit a high degree of porosity and an extended inter-particulate surface area" [21]. The main properties of active carbon are high surface area, well-developed and tunable pores, very reactive surface characteristics, good absorptive capacity, and dependable physiochemical stability [18]. Final active carbon properties strongly depend on the precursor properties, pretreatment of the precursor, and the activation process. The production factor determination depends on the application of the active carbon and its required properties. Active carbon can be manufactured almost from any organic material with sufficient carbon content, making date palm waste a suitable precursor due to the versatility of the waste and its chemical properties.

4.3.1. Active Carbon Production from Date Palm Waste

To produce active carbon, the precursor needs to be carbonized (turn into char) then activated. To improve the active carbon quality and avoid property variations, pretreatment processes are required.

Pretreatment

Suggested date palm pretreatment steps are (a) isolation, (b) washing, (c) drying, and (d) sizing.

(a) Isolation

Date palm wastes usually are not separated during extraction. Leaflets and rachis need to be separated due to the significant differences in their properties. Date palm fruits are not suitable themselves as a precursor for active carbon; only seeds have been used by researchers. However, date seeds are the main waste of date processing industries.

(b) washing:

Date palm waste is usually left on the soil after extraction, causing leaching and absorbing soil minerals and other chemicals, which affects the calorific value of the waste. Washing needs to be done in two phases: washing and soaking with water to remove soil, dust, nylon, ash particles, and any particles that are not chemically pounded to the waste. The second phase is washing with a weak acid that dissolves any chemically bounded pollution and undesirable particles such as ash. Acid washing also helps to dissolve some of the extractive as violate fat. Ash particles significantly affect the active carbon quality, which is why washing is important to ensure efficient active carbon. Abdullah and Sulaiman [47] studied the effect of washing on ash removal, and their work results are in Table 8. Washing procedures can be much easier and cheaper by properly harvesting the date palm residue as a raw material, not as waste. This is done by collecting fronds in the warehouse directly instead of leaving them on the soil under climate conditions.

Table 8. The effect of water washing on ash content [18].

Treatments	Soak Time (min) Ash	Amount of Water (L)	Content (mf wt. %)
No.	Untreated	Untreated	5.19
1	5	5	2.66
2	10	5	2.21
3	20	5	1.66
4	30	5	1.54
5	5	3	2.98
6	10	3	2.59
7	15	3	2.43
8	20	3	2.17
9	25	3	1.97
10	30	3	1.89
11	5	2	3.19
12	5	2.5	3.15
13	5	3	2.98
14	5	3.5	2.82
15	5	4	2.79
16	5	5	2.66
17	10	5	2.14
18	1	5	3.68
19	20	5	2.14
20	1440	7	1.03

(c) Drying:

The aim of the drying process is to remove moisture and extractive content, which can be done by the sun or oven. Puligundla et al. [23] studied the possibility of using microwaves to dry lignocellulosic biomass, and they recommended oven drying due to its relatively better controllability, easy operation, reliable heating efficiency, and speed [24].

(d) Sizing:

The size of the precursor directly affects the final size of active carbon particles. Sizing is done by first crushing the precursor and then sieving it to avoid particle size variability.

4.3.2. Activation Methods

There are two main activation methods: (1) physical activation and (2) chemical activation. Each method directly affects the properties of active carbon.

(1) Physical activation:

Also known as "thermal activation", this is a double stage pyrolytic process involving carbonization and activation [18]. The first stage, carbonization, is similar to char production; it aims to convert the precursor into carbon while removing any water content, organic acid, and volatile compounds that were not removed by the pretreatment. In addition, carbonization initiates surface area and pores. The second stage is activation, where the carbonized char is reacted with steam, gas, or a mixture of steam and gas to optimize the initiated surface area in the first stage and create new pores. Most researchers suggest the use of CO_2 as activation gas [18].

(2) chemical activation:

Also known as "wet oxidation", this is a single-stage activation process that uses a chemical additive to carbonize and activate the precursor at low temperatures, compared to the physical activation. Chemical activation consumes less time and energy compared to physical activation [18].

4.3.3. Applications of Date Palm Active Carbon

Active carbon has versatile applications. It can be used as gas adsorption, water treatment, gas mask, food decolonization and deodorization, and electrode material of super capacitors. Kyaw et al. [23] successfully manufactured active carbon from date palm leaflets using chemical activation to produce effective active carbon to be used as multi-functional electrodes in capacitive deionization system to be used in water desalination. Their system was able to remove salt ions and degradation and remove dye molecules [22]. Haimour and Emeish successfully manufactured active carbon from date seeds by physical activation, but the active carbon could not meet ASTM standards [21]. Muhammad Vohra was able to treat gas emissions with date pits, chemically activated with active carbon, to treat ammonia-polluted gases [48].

4.4. Water Desalination and Depolluting

About 70% of our planet is covered by water, and only 2.5% is fresh water. However, only 20% of the fresh water is in usable liquid form [49]. Fresh water is not only used for drinking but also used in daily life cleaning and in industrial applications. Such usage pollutes the water, sometimes with toxic organic or inorganic material, including heavy metals. Industries were disposing polluted water directly to the rivers or seas due to the high cost of desalination processes that require expensive materials. Researchers are demanding to study the agricultural waste potential to be used as low-cost absorbents of organic and inorganic pollution. Researchers [14,32,34,47,50,51] have proved the efficiency of date palm fiber and seed waste as absorbent for many pollutants. Most of the mentioned research has been applied in the Gulf countries due to the significant need for water desalination and the availability of date palm.

4.4.1. Preparation of the Date Waste to Be Used as Adsorbent

Researchers used biochar or activated carbon based on date palm waste. Most of them used the date seed as a raw material, turned it into biochar, then crushed it into powder or activated it into active carbon. Muhammad et al. used the date palm fiber that was gathered in the trunk, cleaned the date palm fiber, dried it, then crushed the processed fiber into powder [33,34].

4.4.2. Date Palm Waste Applications in Water Desalination

Research has proved the date palm waste to be an efficient adsorbent due to the favorable chemical composition and the great potential as a precursor for biochar and active carbon. Researchers have studied and approved the date palm waste efficiency as an adsorbent in the following desalination applications:

(1) Removal of Heavy Metal:

Due to the Industrial Revolution, natural water resources have been polluted with heavy metals such as zinc, cadmium [33,39–41], copper [51], lead [32,52], boron [50], arsenic [34], and others. The WHO made guidelines for the maximum amount of each of the heavy metals in drinking water to be safe for consumption. Following that guideline, a lot of researchers investigated the efficiency of date palm waste to absorb heavy metals. They mostly focused on the date seed due to its favorable surface functional group (a chemical property that is responsible for binding with ions) [51].

(2) Dye removal:

Dyes are used in many industries such as textiles, paper, rubber, plastics, leather, cosmetics, pharmaceuticals, food, and paint. The wastewater from such industries contains dye residues. Dyes are classified as anionic (direct, acid, and reactive dyes), cationic (basic dyes), and nonionic (disperse dyes) [47]. Due to the huge diversity of chemical compositions, researchers were working on one dye in each study. However, they proved the ability of date seeds to absorb dye particles. For example, Banat et al. studied raw and activated date pits carbon as an adsorbent for methylene blue dye particles in water [53]. Mahmoodi et al. investigated the removal of the dyes acid green 25, acid black 26, and acid blue 7 using raw date stones [54].

(3) Phenolic pollution removal:

Phenol is any family of organic compounds characterized by a hydroxyl (—OH) group attached to a carbon atom that is part of an aromatic ring. Besides serving as the generic name for the entire family, the term phenol is also the specific name for its simplest member, monohydroxybenzene (C_6H_5OH), also known as benzenol, or carbolic acid. Phenolic pollution sources are not only man-made but also natural. Natural sources of phenolic compounds in water pollution include decomposition of dead plants and animals (organic matter) in the water or synthesized by microorganisms and plants in the aquatic environment. Phenol is also used in many industrial and agricultural applications. Phenol is used in pesticides, paints, solvents, pharmaceuticals, petroleum, and petrochemical industries. The wastewater of such industries is polluted by phenol. Phenol is a highly toxic material; it can enter the human body by drinking water or even by direct contact with skin in high concentration and can cause skin burns and damage to the heart, liver, kidney, muscles, and gastrointestinal system [55].

Researchers have studied the ability of raw date seed powder [56] and activated date pit carbon [53] to absorb phenolic pollution from the water and proved its efficiency. Banat et al. found that the adsorption capacity of date pit activated carbon was 16 times more than that of raw date pits as an adsorbent [57].

(4) Pesticides removal:

Due to agricultural practices, pesticides have become one of the most dangerous water pollutants because of their mobility and tendency to accumulate in living organisms when ascending through the food chain [58]. El Bakouri et al. [59] studied the potential applicability of treated date stones for removing drin pesticides (aldrin, dieldrin, and endrin). They reached a maximum removal efficiency of 93% [59]. Ashour also studied the ability of activated carbon produced from date pits to absorb Pendimethalin, which is an herbicide to control unwanted plants. Ashour proved that date pit activated carbon had high adsorption capacities towards pendimethalin removal [60].

4.5. Other Potential Applications

The applications discussed previously are not the only applications of palm waste. There are other unconventional applications researchers have studied. Some examples are as follows:

- Porous nano-sheet simultaneous determination of dopamine and uric acid:

Ahammad et al. [61] were able to detect dopamine and uric acid levels in the human body even in the presence of interfering species. Such detection is important to diagnose some neurological disorders such as Parkinson's and Alzheimer's.

- Sound absorption made of date palm fiber:

Due to the hollow structure of date palm fiber, it poses good acoustic insulation ability. Taban et al. [62] used date palm fiber to manufacture acoustic insulation panels that can be used to insulate buildings. Their approach offers efficient, low-cost, degradable acoustic insulation panels compared to conventional panels made of synthetic fibers.

- Production of fructose sweetener:

Putra et al. [63] extracted fructose sweetener from date fruit waste using elective fermentation. Due to its high sweetness and solubility, fructose is an important sweetener in beverages and the food industry. Utilizing date fruit waste to extract fructose is an economical approach because it is waste in the first place.

- Production of glucose and lactic acid:

Similar to Putra et al., Azam and Ahmad [64] suggest using date palm waste to produce glucose and lactic acid by transforming cellulose, that date palm waste is full of, to glucose or lactic acid by the help of microorganisms and bacteria.

- Biofuel source:

Due to the finite amount of petroleum and the pollution when producing or using fuel extracted from it, biofuel is a solution researchers and engineers have offered as replacement for petrol [65]. Lattieff [4] was able to produce biogas that can be used as fuel from date palm fruit waste using anaerobic digestion. He proved the suitability of date fruit waste as a biogas source.

Galiwango et al. [66] used direct catalytic depolymerization of lignocellulose from date palm waste to produce liquid fuel. Kamil et al. [67] used date fruit seeds to produce biodiesel. They were able to produce DSO biodiesel using a Model B-811 Extraction System (BUCHI). After extraction, they prepared blends of biodiesel and petrol diesel, and they tested it using a single-cylinder CI diesel engine. Results showed that their blend produced lower levels of CO_2, CO, and HC but higher levels of NO_x emissions. Martis et al. [68] studied the economic feasibility of date palm waste as biofuel source in UAE by simulating three production methods: pyrolysis, gasification, and fermentation. Their study showed that pyrolysis and gasification are economically more feasible than fermentation. Table 9 summarizes some applications of date palm waste and their main products.

Table 9. Summarization of date palm waste applications and their main products.

Application	Products	References
Natural fiber composites (NFC)	Polypropylene composites Epoxy composites Oriented strand board Medium-density fiberboard (MDF) Particle board from date palm Gypsum board reinforcement	[25,31] [27,40] [20] [41] [16,26,42] [43,44]
Biochar	Fertilizer	[16,45]
Active carbon	Gas absorber Water treatment Electrode material of super capacitor	[48] [47] [21]

Table 9. *Cont.*

Application	Products	References
Water Desalination and depolluting	Heavy metal filters Dyes removal Phenolic pollution removal Pesticides removal	[32–34,47,51,52] [53,54] [53,56,57] [59,60]
Food industries raw material	Fructose sweetener Glucose and lactic acid	[63] [64]
Biofuel source	Biogas Liquid fuel	[4] [66]
Other applications	Porous nano-sheet simultaneous determination of dopamine and uric acid Sound absorber	[61] [62]

5. Conclusions and Recommendations

Date palm waste is a huge pollution source in the MENA region due to the huge amount of waste generated by numerous date palm trees planted in the region. Despite the high value of date palm waste chemical materials and extensive mechanical and physical properties of its fiber, the processing procedure is still developing for many applications.

The utilization of date palm fruits and seeds has been explained in many studies for several applications such as active carbon, water depolluting, biochar, biofuel, and more. Unfortunately, date palm waste fiber is not utilized sufficiently, as no research studies about the decorticating of palm waste are available in the literature. As mentioned earlier, fibrous waste is the main waste of date palm in the form of fronds. Researchers studied the application of date palm fiber by using laboratory equipment to prepare the fiber, using the DPF (the naturally separated fiber that grows below the fronds surrounding the trunk) or without explaining the processing method. Industrial-level, highly efficient fiber extraction from date palm waste (especially from fronds) with minimum fiber damage still requires additional studies to be economically and mechanically feasible. Date palm waste is a valuable raw material for numerous applications, as researches sufficiently proved the feasibility of various palm waste as raw material for various applications in many fields. Engineers and scientists need to study processing methods that are feasible for industries with reasonable cost to extract the raw materials with defined properties. Such studies will enable the industries to turn harmful waste into wealth that support countries' economies.

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