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REVIEW PAPER

Review on cellulosic fibers extracted from date palms (*Phoenix Dactylifera* L.) and their applications

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Abstract The increasing demand for more sustainable and renewable materials, has increased the interest in natural fibers. Natural fibers are not only environmentally-friendly, but they also have high specific properties, due to their light weight. The date palm tree (*Phoenix Dactylifera* L.) is considered one of the sources of natural fibers. Fibers could be extracted from different parts of the date palm, namely, the midribs, spadix stems, leaflets, and mesh. The high population of date palm results in huge quantities of by-products of annual pruning, which makes it one of the most available sources of natural fibers. Reviewing the literature showed a need for clarification and analysis. This work offers a thorough and integrated review of prior and current literature related to date palm fibers; their extraction techniques, characteristics, and, applications. This review will provide researchers with a better understanding of date palm fibers and will help them spot the research gaps on which they will build their future research studies. Moreover, this review will help practitioners determine how to use these fibers in producing new materials.

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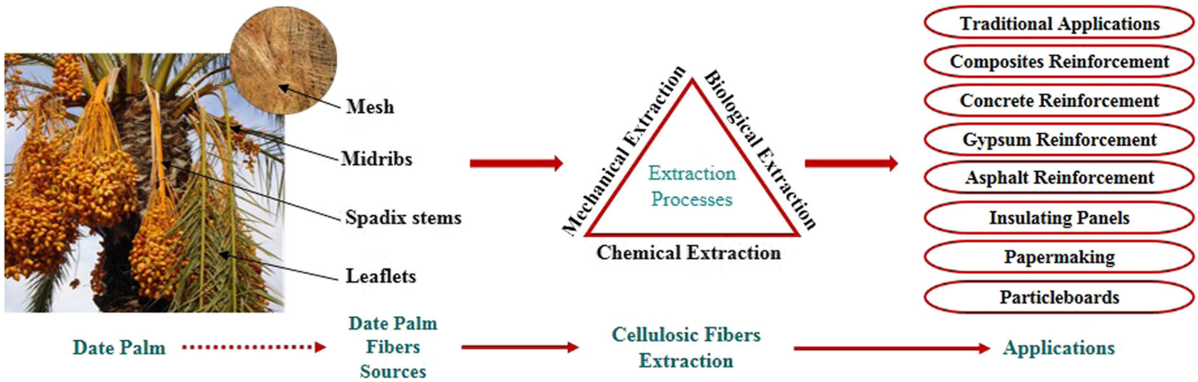
Graphical abstract



Keywords Date palm fibers · Fiber extraction · Natural fibers · Green composites

Introduction

Fibers can be defined as objects that have high aspect ratio (length/diameter) (Stokke et al. 2013). They can be classified into natural and man-made fibers. Natural fibers are obtained from natural sources. There are two types of natural fibers; protein fibers which are obtained from animal resources, such as silk, wool and hair, and cellulosic fibers which are obtained from plants, such as flax, jute, date palm and cotton (Hakeem et al. 2014). Cellulosic fibers can be classified based on the part of the plant from which they are extracted, for instance, fibers extracted from the stem are classified as bast fibers, whereas fibers extracted from the leaves are classified as leaf fibers. In addition to other parts of the plants, such as, seed, fruit, stalk, or grass as shown in Fig. 1.

Cellulosic natural fibers, which are also called lignocellulosic fibers, consist of three major organic constituents; cellulose, hemicellulose, and, lignin. This structure is thought to be like a composite; where cellulose is surrounded by hemicellulose and embedded in lignin as a matrix as shown in Fig. 2 (Stokke et al. 2013). Lignin, is an amorphous organic polymer that consists of aromatic structures in addition to aliphatic chains. Lignin acts as a natural glue, and it binds the cellulose fibers together. Its weight fraction is 10–25% for non-woody plants and 20–30% for woody plants. The hemicellulose acts as the bridge between cellulose microfibrils and lignin. As for cellulose, it's composed of many glucose anhydride molecules linked together by covalent bonds. It has weight fraction that ranges from 30 to 45% (Hakeem et al. 2014). Native cellulose which is originally found in plants is cellulose I, while regenerated cellulose is called cellulose II. Cellulose I is a crystalline material which is formed of parallel chains oriented in the same direction with amorphous regions between the crystalline regions as shown in Fig. 2. The chemical structure of cellulose consists of satisfied OH groups which reduce its moisture absorption; thus, making cellulose less hygroscopic. One of the interesting facts about cellulose is that it can't be dissolved by alkaline solutions and it has high resistance to dissolution by acids with an exception of strong acids at high concentrations. Therefore, cellulose is a chemically stable material unlike lignin or hemicellulose (Stokke et al. 2013). And as mentioned above, cellulose has compact crystalline structure which makes it the load-bearing component in the plant cell; it's what gives the fiber its strength (Nishino 2017). However, natural fibers have a hollow structure due to the presence of what is called lumen. Lumen helps in water absorption and locking water inside the fibers; hence, causing fibers swelling. Fibers swelling is always avoided because it causes micro-cracks in fibers (Hakeem et al. 2014).

Natural fibers could be classified into two other types. First, fibers that are present in fiber form. Second, fibers embedded in a natural matrix. Fibers of the first type are used right away since they are already found in fiber form, they don't need further extraction, they may only require washing, drying then cutting.

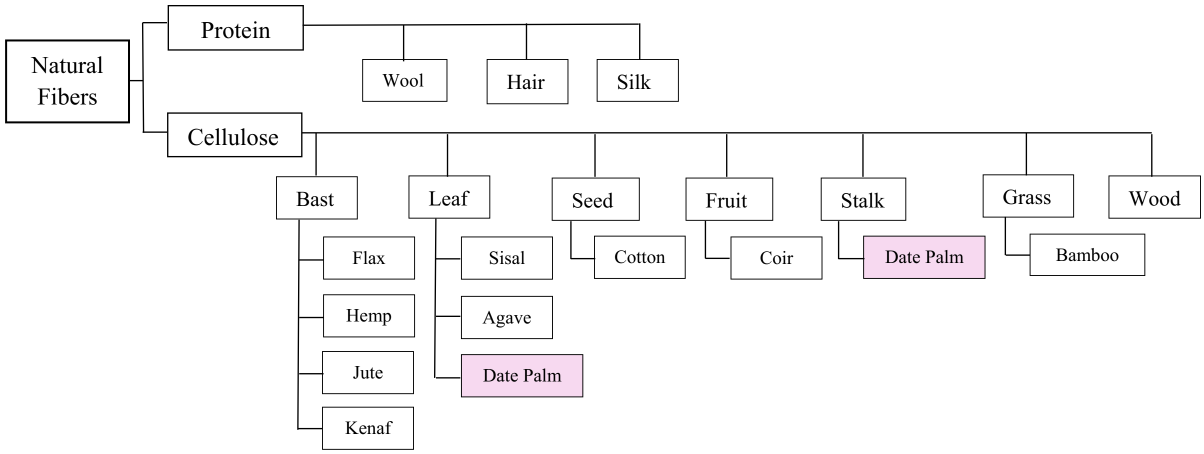


Fig. 1 Natural fibers classifications showing the sources of date palm fibers (Al-Oqla et al. 2014)

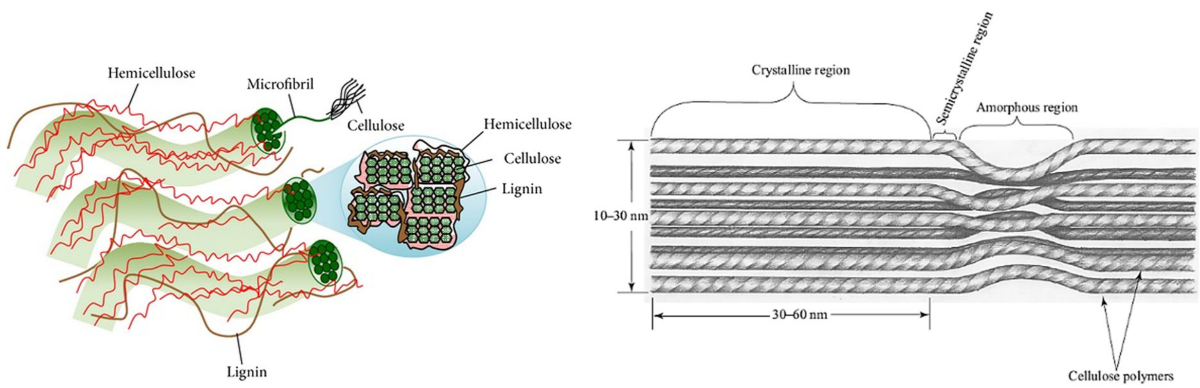


Fig. 2 Microstructure of natural cellulosic fibers (Lee et al. 2014) and Cellulose polymer chains showing cellulose crystalline and amorphous regions (Stokke et al. 2013)

However, the second type requires further processing through many extraction or separation approaches. These approaches could be chemical, biological, or, mechanical (Hakeem et al. 2014; Nishino 2017).

There are two major influencing factors which affect the performance of natural fibers in general. First, factors that could be controlled like cultivation factors, extraction process parameters and fiber treatment conditions. The cultivation factors are mainly soil quality, climate and weather conditions, fertilization, and fiber location on the plant. The extraction process parameters and treatment conditions include the extraction technique, the drying temperature, the type and concentration of the chemical solution used. Second, factors that cannot be controlled include the natural defects in the fibers, microfibrillar angle (MFA), chemical composition (the wt% of each constituent), cell dimensions and structure (Hakeem et al. 2014).

One of the plants which is rich in fibers is the date palm tree (*Phoenix Dactylifera* L.) (DP) which is also known as the true date palm, since it is the only species that produces date fruits. Fibers can be obtained from four parts of the date palm, they could be extracted from the mesh, the spadix stems, the midribs and the leaflets as shown in Fig. 3. In botany there are two types of leaves in general; simple leaf and compound leaf. The simple leaf doesn't have many leaflets; it only has one part supported by the petiole as shown in Fig. 3. On the other hand, the compound leaf has many leaflets attached to the inner stem. The leaf of a date palm is a compound leaf and it is divided into three parts; the midrib, midrib base and the leaflets. The anatomy of date palm leaf is shown in Fig. 3. The

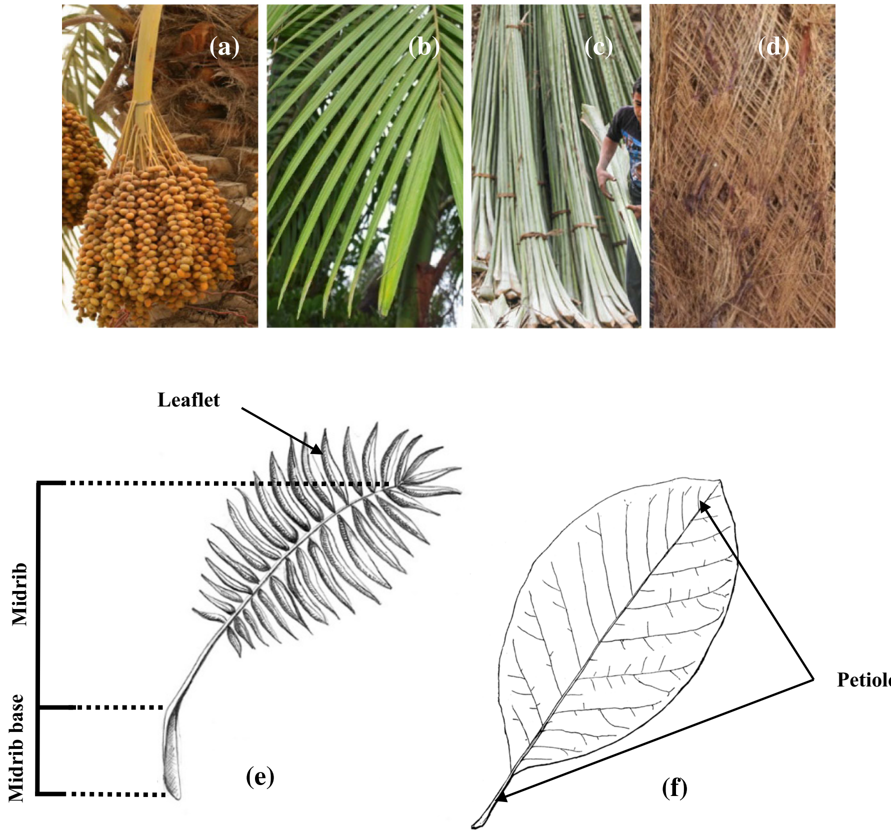


Fig. 3 Date palm parts **a** spadix stems **b** leaflets **c** midribs **d** mesh in addition to **e** date palm leaf anatomy compared to **f** simple leaf anatomy (Newhall 1891)

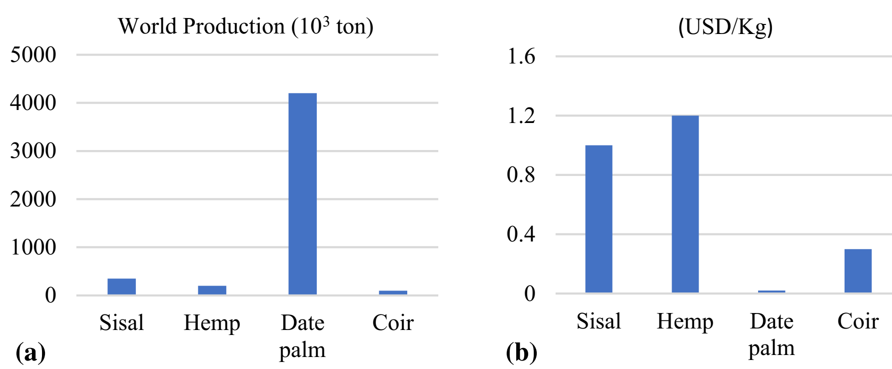


Fig. 4 **a** The annual world production of natural plants and **b** prices of some natural fibers compared to date palm (Al-Oqla and Salit 2017)

midrib is sometimes referred to as rachis or petiole and it is the center part that carries the leaflets. The mesh is sometimes referred to as tree surface, bark, and sheath.

The world production of natural fiber sources and their cost play an important role in the material selection process. Date palm is considered one of the most available natural fiber sources as shown in Fig. 4a. Moreover, it is very cheap in comparison with other natural fiber sources as can be seen in Fig. 4b (Al-Oqla and Salit 2017; Midani 2017). The number of trees that are cultivated in the Arab countries are shown in Table 1. The total number of date palm trees cultivated, according to a count by El-Juhany in 2007, was nearly more than 85 million trees (El-Juhany 2010). Moreover, according to a study made by El Mously in 1995, it was found that a single female date palm tree produces annually a dry weight of 9.75 kg of

Table 1 Number of productive date palms and area in the Arab countries for 2007 and the annual pruning of a single date palm (El-Juhany 2010; El-Mously 2005)

Country	No. productive trees (× 1000 trees)	Amount (tons)			
		Midribs	Spadix stems	Leaflets	Mesh
MENA region	82,100.08	800,475.78	574,700.56	656,800.64	102,625.1
Mauritania	600	5850	4200	4800	750
Sudan	2646	25,798.5	18,522	21,168	3307.5
Total	85,346.08	832,124.28	594,722.56	682,768.64	106,682.6

midribs, 7 kg of spadix stems, 8 kg of leaflets, and, 1.25 kg of mesh (El-Mously 2005).

Aside from the large availability of date palm fibers in comparison with other natural fibers sources as discussed earlier, date palm fibers also exhibit desirable physical, mechanical, and, thermal properties as will be discussed later.

Fiber extraction

There are several techniques reported in literature to extract fibers from different parts of the date palm. Each technique has its own advantages and limitations. Some authors mechanically extracted the fibers while others used chemical or biological treatments to separate cellulose fibers from other constituents, such as, lignin and hemicellulose.

The fiber extraction technique is one of the most important factors in obtaining high performance fibers. The fiber extraction is considered successful if it yields pure, long, and fine fibers with minimal fiber damage. The most frequently used techniques in literature are the mechanical extraction and the alkaline treatment with NaOH.

Mechanical extraction

Many studies were based on chopping and grinding date palm parts without any attempts to delignify the fibers. Date palm parts were cut into very small pieces; this method of separation was adapted by many researchers (El-Morsy 1980; Khristova et al. 2005; Sbiai et al. 2008; Alawar et al. 2008; Nasser and Al-Mefarrej 2011; Saadaoui et al. 2013; Amirou et al. 2013; Mirmehdi et al. 2014; Nasser 2014; Hosseinkhani et al. 2014; Alajmi and Shalwan 2015; Chaib et al. 2015; Al-Otaibi et al. 2016; Nasser et al. 2016; Boukhattem et al. 2017; Boumhaout et al. 2017; Masri et al. 2018).

In other studies, the date palm parts were used without extraction either by shredding or by using full parts. This was mainly used with date palm leaflets; where the leaflets were manually shredded into thin parts or full leaflets and used as composites reinforcement (Al-Sulaiman 2002, 2003; Sbiai et al. 2011; Al-Rifaie and Al-Niami 2016). As for the mesh fibers, they were manually separated either by hand or in water, and this method of separation was only used with mesh fibers (Kriker et al. 2005; Rao and Rao 2007; Shalwan and Yousif 2014; Mokhtari et al. 2015; Ali and Alabdulkarem 2017; Oushabi et al. 2017; Tioua et al. 2017). Mesh fibers exist in a form that make the separation of fibers seems easy as shown in Fig. 3d.

Chemical extraction/treatment

The most commonly used chemical treatment method was the alkaline treatment specifically by NaOH. Table 2 shows the chemical treatment of date palm fibers using NaOH at different concentrations, treatment duration and treatment temperature specifying which date palm part was used to extract fibers. The most frequent NaOH combinations used were 1% NaOH at 100 °C for 1 h and 5% NaOH at 90 °C for 3 h. The first combination rendered the highest mechanical properties of fibers in a study by Alawar et al. (2009).

Yet, other researches tried other alkaline solutions to extract date palm fibers. El-Morsy as well as Kriker et al. used $Ca(OH)_2$ (El-Morsy 1980; Kriker et al. 2008). Abdel-Rahman et al. used cement solution which is considered an alkaline medium to treat fibers

Table 2 Alkaline treatments of date palm fibers using NaOH in the literature

Date palm parts	NaOH (%)	Duration (h)	Temperature (°C)	References
Midribs	8, 12	2, 3	100	El-Morsy (1980)
Spadix stems	5	3	90	Ibrahim et al. (2014)
	0.5, 1, 2, 3	12, 24, 48, 72, 96	23	Ibrahim et al. (2017)
	2, 5	2, 4, 6, 24	0	Amroune et al. (2015)
	10	24	0	AlMaadeed et al. (2013)
	5	3	80–90	Abdelaziz et al. (2016)
Leaflets	0.5, 1, 2, 3	2	100	Taha et al. (2007)
	1	1	80	Zadeh et al. (2017)
	5	1	100	Dehghani et al. (2013)
	5	1	80	Mohanty et al. (2014)
Mesh	6	24	Room temp.	Shalwan and Yousif (2014)
	5, 2.5, 1.5, 1, 0.5	1	100	Alawar et al. (2009)
	3, 6, 9	24	Room temp.	Alsaeed et al. (2013)
	1	1	100	Elbadry (2014)
	5	3	90	Saleh et al. (2017)
	5	2	100	Al-Kaabi et al. (2005)
Unspecified	0, 2, 5, 10	1	25	Oushabi et al. (2017)

(Abdel-Rahman et al. 1988). Additionally, Pandey et al. used Textone solution (Pandey and Ghosh 1995). Moreover, Abdelaziz et al. (2016) used CaO. Another alkaline solution was a mixture of a commercial detergent and a dioxine solution used by Al-Kaabi et al. (2005).

On the other hand, there were several attempts by researchers to use acidic chemicals for treatment. HCl solution was used by Alawar et al. (2009). Three studies used a mixture solution of glacial acetic acid and hydrogen peroxide (Mahdavi et al. 2010; Abdel-Aal et al. 2015; Hegazy and Ahmed 2015). Acrylic acid was used as treating solution by Mohanty (2017), while Jaber et al. used 10% nitric acid and 10% chromic acid (Jaber et al. 2016). In a study by Taha et al. more than one chemical treatment processes were made (Taha et al. 2006). They treated the fibers with a mixture of toluene/methanol/acetone (tma), CCl_4, NaOH, and, $NaC_{12}H_{25}SO_4$ separately at different concentrations and treatment durations. A mixture of ethanol/toluene was used by Abu-Sharkh and Hamid (2004). Other chemical extraction process is the TEMPO mediated oxidation where fibers are oxidized using TEMPO as a primary oxidant which was used by Sbiai et al. (2011) to extract cellulose fibers from DP. Finally, one of the uncommon techniques used in the literature to treat fibers' surface was the use of oxygen plasma at different plasma power and exposure durations (Gholami et al. 2017).

Biological extraction/treatment

The biological extraction techniques could be classified into two types; retting and enzymatic treatment. First, retting process was used by Rao et al. by soaking the fibers in water for long period of time, then mechanically extracting them (Rao and Rao 2007). This water soaking technique was also used by Ibrahim et al. and Neher et al. (Ibrahim et al. 2014; Neher et al. 2016). As for enzymatic treatment, Hassan et al. used xylanase enzymes, and, Tahri et al. used enzymatic treatment without mentioning enzyme type (Hassan et al. 2014; Tahri et al. 2016).

In 2017, Midani tried a novel process/technique (2017). The extraction process aimed at fibrillating the brittle vascular fiber bundles and changing them into thin flexible fibers to produce woven preforms. The author highlighted the importance of using long treated fibers as reinforcement in composites instead of the short-chopped ones. Moreover, this is nearly the very first study that investigated the subject of fiber-extraction from the point of view of eliminating the voids inside the fibers and producing long cellulose microfibrils. Most of the prior literature approached the subject of fibers extraction in a limited way, since the extracted fibers were mainly chopped into very short fibers. Moreover, the chemical analysis of fibers in the literature showed that there is a large amount of lignin and hemicellulose sticking on the surface as will be discussed later.

Post extraction analysis

FTIR tests have been performed in several previous research work to determine the efficiency of the extraction process in removing the lignin and the hemi-cellulose contents by observing the peaks of their functional groups. The analysis has been performed on the fibers extracted from the spadix stem, leaflets and mesh.

Taha et al. investigated the fibers extracted from the spadix stems and they reported that the alkaline treatment of the fibers resulted in an increase in the O–H which was assumed to be due to the breakage of hydrogen bonding in cellulosic hydroxyl groups. Moreover, the authors observed that the C=O (ester groups) and the aromatic C=C groups disappeared completely when the fibers were treated with NaOH which suggested that the alkaline treatment removed the fatty acids and all oil traces from the fibers surface. Furthermore, they found that the alkaline treatment had no significant effect on removing lignin while it had a significant effect on removing the hemicellulose (Taha et al. 2007). This confirms that further processing of the fibers after treatment is required. For the same fibers type, spadix stems fibers, Amroune et al. studied the effect of NaOH treatment on the removal of lignin and hemicellulose. It was observed that the chemical treatment reduced the effect and number of O–H links. Moreover, the authors noticed that there wasn't much difference between treated and untreated fibers (Amroune et al. 2015). No FTIR analysis were performed on fibers extracted from the midribs in the literature.

The FTIR results of leaflets fibers showed a stretching in the C-H band due to the presence of ester groups as a result of the acidic treatment by acrylic acid (Mohanty et al. 2014). However, when leaflet fibers were chemically extracted by TEMPO mediated oxidation method a stretch in the C=O band was observed indicating the oxidation of fibers and the degree of oxidation was 0.71 ± 0.02 (Sbiai et al. 2011). In a study by AlMaadeed et al., the FTIR analysis was made on treated and untreated leaflet fibers and compared to each other. It was observed that the NaOH alkaline treatment has made the peaks less sharp and reduced their intensity indicating that these leaf fibers had lower hydrogen bonding. Moreover, the carbonyl group intensity that corresponds to hemicellulose was found to have decreased after the chemical treatment. This decrease in the intensity is due to the removal of hemicellulose and lignin content from the fibers' surface. The authors claimed that the alkaline treatment has caused the leaflet fibers to lose their crystalline structure (AlMaadeed et al. 2013). The results of AlMaadeed et al. were in agreement with the results obtained by Dehghani et al., they found that the alkaline treatment by NaOH caused reduction in the O–H peaks and this was attributed to the reduction in the number of OH groups on the surface. Moreover, there was an absorption in the C=O band due to the removal of hemicellulose by the chemical treatment (Al-Maadeed and Labidi 2013; Dehghani et al. 2013).

As for mesh fibers, the FTIR results obtained by Alawar et al. showed that the NaOH treatment caused an absorption in band of the C=O group which was assumed to be due to hemicellulose removal. However, the authors observed that a significant change in the chemical structure has happened between the treated and untreated fibers (Alawar et al. 2009). The results of Abdal-hay et al. confirmed the previously mentioned results. The C–H and C=O peaks disappeared after the alkaline treatment which is due to the removal of hemicellulose. Moreover, there was an absorption in the band of O–H group; which may be due to the removal of lignin and wax from the fibers' surface. The authors found that the best results were obtained when the fibers were treated with 6% NaOH (Abdal-hay et al. 2012).

Fiber characterization

The fiber characteristics and performance dictate its final application. Thus, it was important to review the fiber characterization results in the literature. The upcoming subsections will discuss and compare the properties and characteristics of date palm fibers obtained from the literature.

Physical properties

The diameter and length of fibers were measured in many studies on the fibers extracted from different date palm parts. Table 3 shows the values of diameter, length, and, aspect ratio measured in different studies. It was noticed that the fibers extracted mechanically from date palm midribs had higher diameter and length values while the fibers extracted with other techniques regardless of their type had lower values. The midrib fibers' bulk density values obtained from two studies were low; Saadaoui et al. reported 0.289 ± 0.018 gm/cm^3 while Abdel-Aal et al. reported 0.13 gm/cm^3 (Saadaoui et al. 2013; Abdel-Aal et al. 2015).

As for the spadix stems physical properties, the values were close to that of the midrib fibers. The treated fibers obviously had lower diameter values compared to untreated ones which somehow could indicate the removal of material surrounding the fibers. The fibers length values weren't in the same range, but this could be due to many reasons, such as, processing parameters, or cutting technique. The bulk density of fibers extracted from the spadix stems was obtained in only one study made by Ibrahim et al. (2017) and it was equal to 1.37 ± 0.009 gm/cm^3.

Table 3 Date palm fibers physical properties

Date palm part	Extraction technique	Diameter (µm)	Length (mm)	Aspect ratio	Bulk density (gm/cm^3)	References
Midribs	Mechanical	13.7–16.6	1.1–1.3	66.3–95	–	Khristova et al. (2005)
		12.79	1.18	92.26	0.13	Abdel-Aal et al. (2015)
		426	–	–	0.289 ± 0.018	Saadaoui et al. (2013)
		510	1.69	3.3	–	Mirmehdi et al. (2014)
	Chemical	10	–	–	–	Agoudjil et al. (2011)
		–	12.8–48.6	–	–	Hegazy and Ahmed (2015)
		14.2–22.6	1.01–1.258	45–89	–	Jaber et al. (2016)
		100	300	3000	–	Midani (2017)
Spadix stems	Untreated	23.4	0.61–0.81	26–34.6	–	Hassan et al. (2014)
	Biological (enzymatic)	20.3–20.6	0.56–0.74	27.18–36.45	–	Hassan et al. (2014)
	Chemical	196 ± 120	13.8 ± 6.5	70–70.4	1.37 ± 0.009	Ibrahim et al. (2014, 2017)
Leaflets	Mechanical	460	3.42	7.43	–	Mirmehdi et al. (2014)
	Biological (retting)	Cross-sectional area = 0.4105–0.5167 mm^2			0.99	Rao and Rao (2007)
	Chemical	8–16	1.5–2.5	150–190	–	Pandey and Ghosh (1995)
		435.2	4.7	10.8	–	Abu-Sharkh and Hamid (2004)
		1000	15	15	–	Mohanty et al. (2014)
		10,000	50	5	–	Mohanty (2017)
Mesh	Mechanical	< 700	20–50	29–72	–	Boumhaout et al. (2017)
		< 700	50–60	< 71.4–85.7	–	Boukhattem et al. (2017)
		100–2000	50–3000	150–3000	0.6–0.7	(Al-Rifaie et al. 2016)
		208 ± 22	–	–	–	Abdal-hay et al. (2012)
		500 ± 50	80	145–160	–	Alajmi and Shalwan (2015)
	Water separation	100–800	10, 20, 30	12.5–300	–	Tioua et al. (2017)
	Chemical	200–800	15–60	18.75–300	0.51–1.09 (bulk)	Kriker et al. (2005)
		181 ± 23	–	–	1.30–1.45 (abs.)	Abdal-hay et al. (2012)

Leaflet fibers physical properties found in the literature had a lot of discrepancies. It was noticed that for the same extraction technique the diameter and length data weren't the same or even within a certain range as shown in Table 3. As for the bulk density, it was only measured in one article by Rao and Rao (2007) and it was found to be equal to 0.99 gm/cm^3.

Finally, the mesh fibers diameters were larger than the other types of fibers. Moreover, no significant effect on fibers dimensions was observed as a result of different extraction techniques; this could be due to the fact that mesh fibers are often found in a fiber form which somehow misled researchers into thinking that they didn't require further processing.

In general, the density of date palm fibers is lower than that of sisal, hemp, and, coir as shown in Fig. 5. The density values are average density values obtained from the literature.

Surface morphology

Table 4 shows the morphology of different date palm fibers before and after treatment presented in 14 figures from Figs. 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 and 19. The techniques used to extract fibers played an important role in the surface topography and the smoothness of fibers' surface. It was observed that the NaOH treatment helped in the removal of lignin and other impurities from the surface as shown in Figs. 8 and 10; also the plasma and acrylic acid treatments were effective in smoothing the fibers' surface. However, some of the extraction techniques in the literature were not successful, for example, mesh date palm fibers were treated with HCl and the vigorous acidic treatment resulted in thinning of the fibers as shown in Fig. 19. In general, date palm fibers consist of vascular bundle of fibers as could be seen in Table 4. Figure 6 shows the cross-sectional view of date palm midrib. However, the shape of these vascular bundles varies depending on the source of fibers. Moreover, some crystals were observed in the surface as shown in Fig. 18. Comparing the crystals to the literature it was found that these crystals are in fact silica crystals (Li 2014).

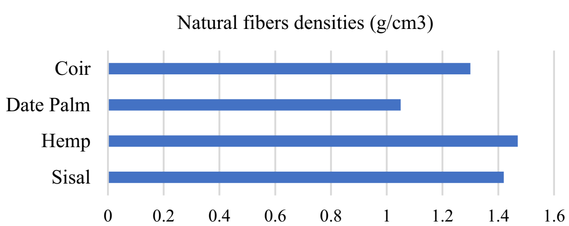


Fig. 5 Comparison between some natural fibers densities in g/cm^3 (Al-Oqla and Salit 2017)

Chemical analysis and microstructure

Chemical analysis and determination of cellulose, lignin, and hemicellulose contents is an important factor to judge the purity of the fibers (cellulose) and the expected yield. Table 5 shows the chemical composition of different date palm parts. It was noticed that the midrib and mesh fibers had the highest cellulose contents. On the other hand, lignin content was within the same range for all the fibers' types. As for the studies comparing between the chemical compositions of different cultivars, it was observed that the composition slightly differs between them (Nasser 2014; Amroune et al. 2015).

The cellulose content in date palm fibers isn't as high as sisal or hemp but still it is better than that in coir and as shown in Fig. 20. Also, what adds to the good properties of date palm fibers is that the lignin content is lower than half its cellulose content. Whereas, the lignin content ranged between 22.53 and 36.73% for the different types of date palm fibers. This reduction in lignin and hemicellulose resulted in lower water absorption %.

The crystallinity index (CI) and XRD tests were performed on different date palm samples. Unfortunately, no XRD test was performed on midrib fibers; thus, there are no estimates of the CI of the untreated or treated midrib fibers. However, some XRD tests were made on the Spadix stem fibers. Figure 21 shows a typical XRD curve of spadix stems fibers treated at different xylanase enzymes concentrations. The curve in Fig. 21 shows the known patterns of cellulose I at two peaks $2\theta = 15°$ (from 1 to 10 and 110 planes) and $2\theta = 23°$ (from 200 plane). These peak labels (Miller indices) are to conform to the required conventions in Cellulose (French 2014) and are not the same as originally reported. The CI of untreated fibers was calculated and found to be 76% and that of enzymatically treated fibers was found to be between 76 and 78% depending on the enzyme concentrations. Hence, the enzymatic treatment hasn't affected the CI of date palm spadix stems fibers (Hassan et al. 2014).

Table 4 Date palm fibers morphology comparison

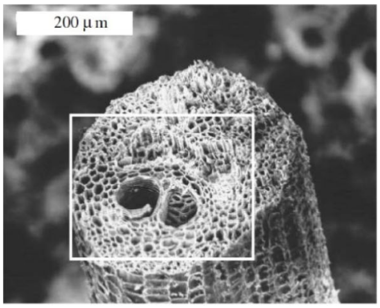
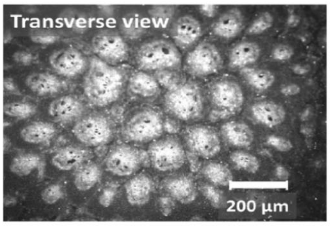
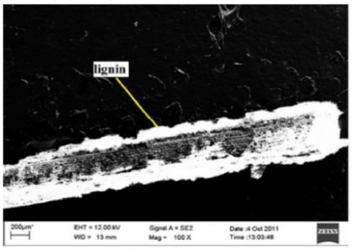
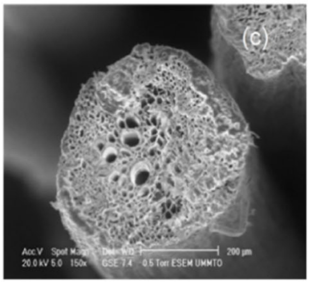
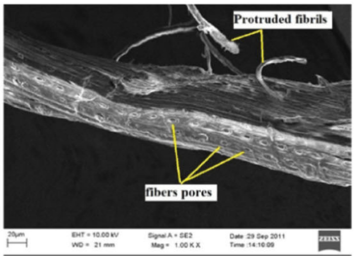
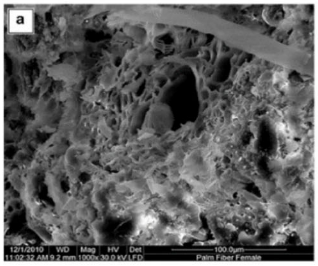
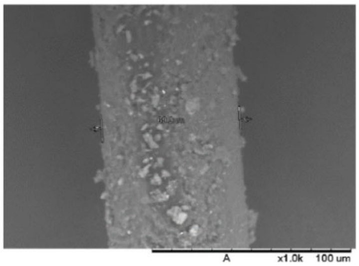
Date pam parts	Extraction technique	Cross-section view	Longitudinal view
Midribs	Untreated	 **Fig. 6** SEM of date palm midribs in the cross-sectional view (Benzidane et al. 2018)	—
Spadix stems	Raw Fibers	 **Fig. 7** Optical micrographs showing transverse view of date palm spadix stems fiber (Abdelaziz et al. 2016)	 **Fig. 8** SEM of untreated date palm spadix stems fibers covered with lignin (Ibrahim et al. 2014)
	NaOH treated fibers	 **Fig. 9** SEM of date palm spadix stems fibers (Amroune et al. 2015)	 **Fig. 10** SEM of date palm treated fibers showing the removal of lignin from the surface (Ibrahim et al. 2014)
Leaflets	Raw Fibers	 **Fig. 11** SEM of untreated female date palm leaflet fiber (AlMaadeed et al. 2014)	 **Fig. 12** SEM of longitudinal view of untreated date palm leaflets fibers (Dehghani et al. 2013)

Table 4 continued

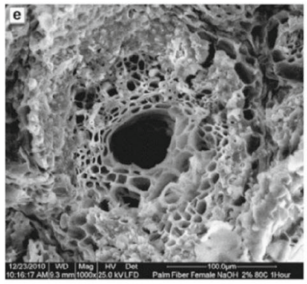
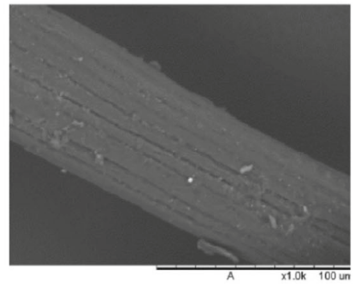
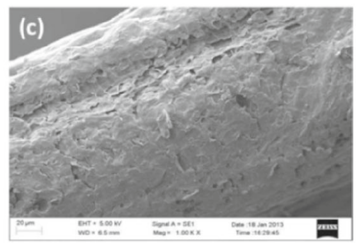
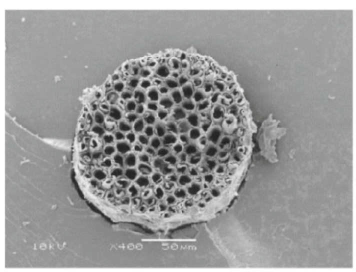
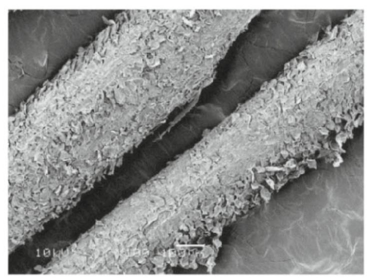
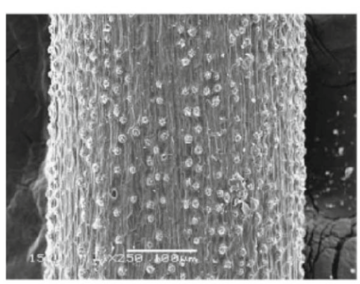
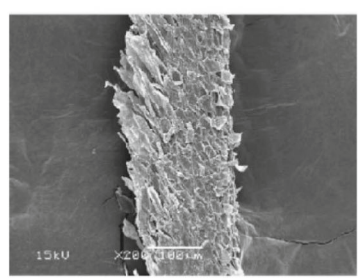
Date pam parts	Extraction technique	Cross-section view	Longitudinal view
	NaOH treated fibers	 **Fig. 13** SEM of female date palm leaflet fiber treated with 2% NaOH (AlMaadeed et al. 2014)	 **Fig. 14** SEM of longitudinal view of NaOH treated date palm leaflets fibers (Dehghani et al. 2013)
	Acrylic acid treated fibers	–	 **Fig. 15** SEM of date palm leaflet fiber treated with acrylic acid (Mohanty et al. 2014)
Mesh	Raw fibers	 **Fig. 16** SEM of date palm mesh showing the cross-section of untreated fibers (Al-Khanbashi et al. 2005)	 **Fig. 17** SEM of date palm mesh fiber's surface (Al-Khanbashi et al. 2005)
	Chemical treatment	Sodium hydroxide  **Fig. 18** SEM for DPF mesh treated with 1% NaOH (Alawar et al. 2009)	Hydrochloric acid  **Fig. 19** SEM of date palm mesh fiber's surface showing the attack caused by the acidic treatment (Alawar et al. 2009)

Table 5 Date palm fibers chemical composition

Date palm part	Cultivar	Cellulose (%)	Lignin (%)	Hemicellulose (%)	Ref.
Midribs	–	45	29.8	29.8	Khiari et al. (2010)
	–	38.26	22.53	28.17	Mirmehdi et al. (2014)
	Barhi	44.14 ± 2.1	25.93 ± 2.8	29.93 ± 1.56	(Nasser 2014)
	Khodry	45.74 ± 1.7	29.37 ± 2.1	24.9 ± 2	Nasser (2014)
	Khalas	44.91 ± 3.8	25.82 ± 3.4	29.27 ± 3.1	Nasser (2014)
	Sukkari	41.63 ± 1.4	30.07 ± 2.5	28.31 ± 2.4	Nasser (2014)
	Sullaj	42.93 ± 2.6	30.09 ± 1.8	26.98 ± 1.2	Nasser (2014)
	–	46.41	–	25.89	Nasser and Al-Mefarrej (2011)
	–	39.8 ± 0.9	14 ± 0.9	31.4 ± 3.2	Saadaoui et al. (2013)
	–	35.87	26.89	28.58	Amirou et al. (2013)
	Sukkari	45.16	26.68	28.16	Nasser et al. (2016)
	Barhi	47.84	29.6	23.1	Hegazy and Ahmed (2015)
	Saqie	48.86	31.28	19.86	Hegazy and Ahmed (2015)
	Sukkari	47.17	30.19	22.3	Hegazy and Ahmed (2015)
Spadix stems	Sukkari	43.05	29.47	27.48	Nasser et al. (2016)
Leaflets	–	40.21	32.2	12.8	Mirmehdi et al. (2014)
	–	29.7 ± 1.3	11.6 ± 1.3	23.3 ± 1.2	Saadaoui et al. (2013)
	Sukkari	47.14	36.73	16.13	Nasser et al. (2016)
	–	58	15.3	–	Pandey and Ghosh (1995)
Mesh	–	50.6 ± 1.3	31.9 0177 1.3	8.1 ± 0.3	Saadaoui et al. (2013)
	Sukkari	47.5	39.86	12.64	Nasser et al. (2016)
	–	48	24	19	Taha et al. (2006)
	–	43 ± 2	35 ± 5	8 ± 2	Mekhermeche et al. (2016)
Stone	–	32.77	37.03	12.64	Nasser et al. (2016)
Trunk	–	43.7	16.94	38.14	Amirou et al. (2013)
	Sukkari	39.37	30.32	30.31	Nasser et al. (2016)

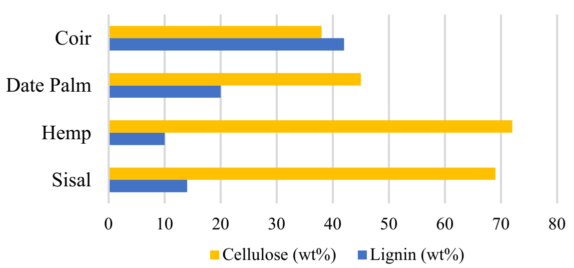


Fig. 20 Comparison between cellulose and lignin contents of some natural fibers (Al-Oqla and Salit 2017)

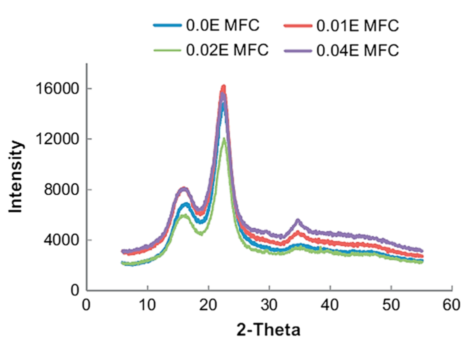


Fig. 21 XRD pattern of isolated microfibrillated cellulose fibers (MFC) from untreated (0.0E), 0.01E, 0.02E, and 0.04E enzymatic treated date palm spadix stem fibers (Hassan et al. 2014)

Mohanty et al. (2014) studied DPL leaflet fibers with diffraction but those results should not be compared with other, typical data. The peak positions are different because a cobalt X-ray tube was used instead of the normal copper tube (a simple conversion is available). The crystallinity index calculations were based on the erroneous proposal that the height of the (1–10) and (110) peaks somehow represents the amorphous content. Although this proposal has been used previously, it is not what Segal proposed. Instead of a peak, Segal proposed that the minimum in intensity between the (110) and (200) peaks represents the amorphous content (Segal et al. 1959; French and Santiago Cintrón 2013; French 2014). Another problem is that the patterns are not clearly cellulose I or another form.

As for mesh fibers, the XRD curve expressed in Fig. 22 shows two peaks at approximately 2θ equals 16° and 22°. The CI was calculated by Abdal-Hay et al. using Segal equation and found to be 19.9% for untreated fibers and 38.5% for NaOH treated fibers. The authors reported that the untreated fibers had amorphous structure due to the presence of hemicellulose (Abdal-hay et al. 2012).

From the previous review, we can conclude that date palm fibers have very competitive properties compared to other natural fibers.

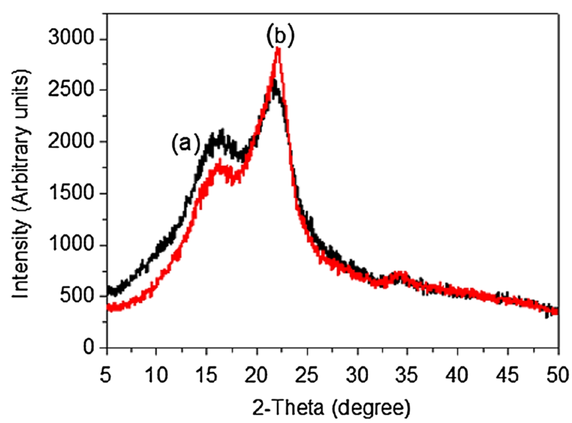


Fig. 22 XRD of **a** untreated and **b** NaOH treated mesh fibers (Abdal-hay et al. 2012)

Mechanical properties

The specific tensile strength and modulus of date palm fibers were compared in the literature to other natural fibers which is shown in Fig. 23. Date palm fibers have specific tensile strength higher than bamboo, coir, sisal, and, banana fibers. While, the specific modulus of date palm is nearly equal to that of flax fibers (Midani 2017). The extraction technique has a significant effect on the mechanical properties of fibers. It was noticed that extracting the fibers using NaOH has improved the mechanical properties. However, the tensile and elastic moduli are different from each other, with the elastic modulus being much greater numerically. This could be due to many reasons related to the treatment duration, temperature, and, NaOH concentration. Moreover, Fig. 24 shows the elongation to break % of date palm fibers and it was found to be higher than that of sisal and hemp but lower than that of coir. Table 8 shows a comparison between the mechanical properties of date palm fibers extracted from different parts. Unfortunately, the values found in the literature aren't within a certain range or close to each other. Moreover, there isn't any reliable source that provided tensile strength, young's modulus, or, tensile strain of date palm fibers to be able

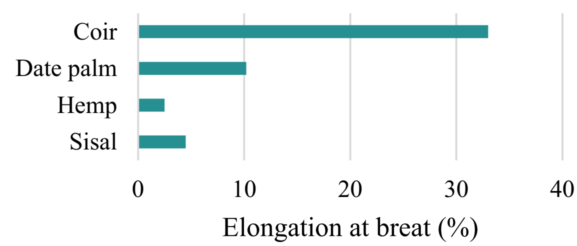
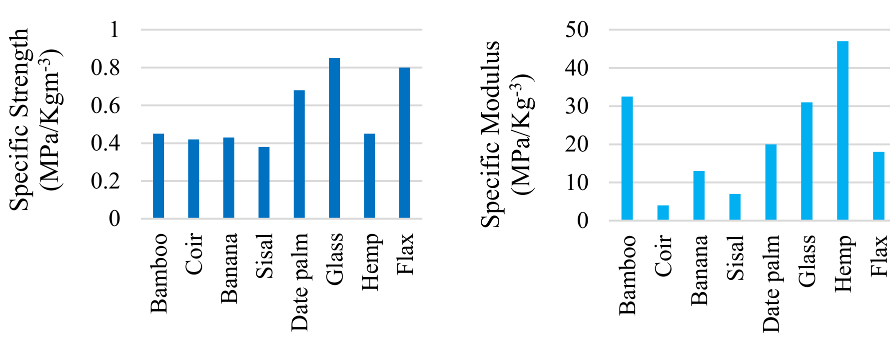


Fig. 24 Comparison between some natural fibers elongation at break percentage (Al-Oqla and Salit 2017)

Fig. 23 Comparing the specific tensile strength and modulus of natural fibers, date palm, and, glass (Midani 2017)



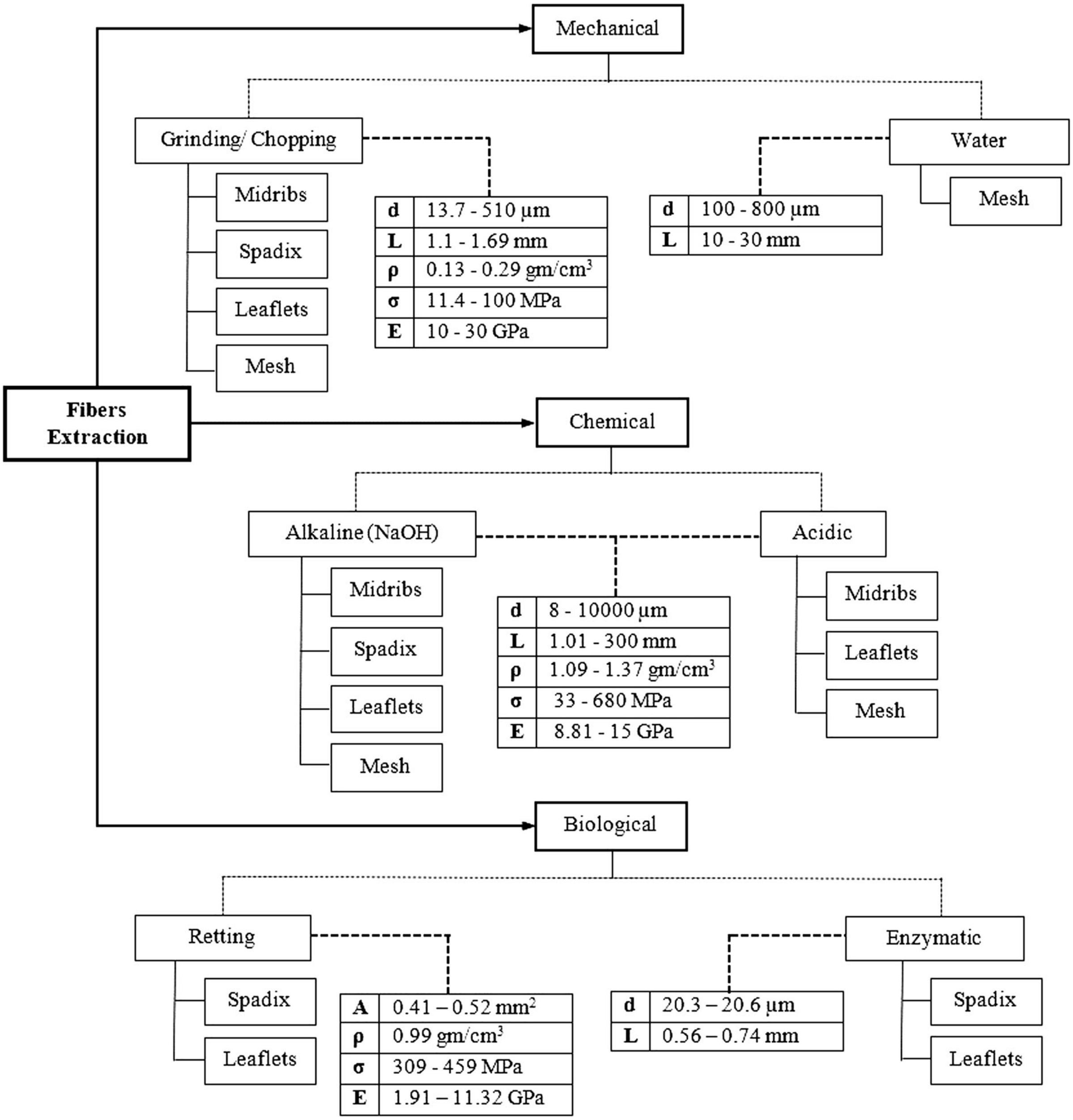


Fig. 25 Classification of extraction processes showing fibers' source from date palm and their physical and mechanical properties (*d* diameter, *L* length, ρ density, σ tensile strength, *E* modulus of elasticity, and *A* cross-sectional area)

to compare the results. And this could be due to the fact that the fibers extracted in the literature were mostly chopped or cut into very short fibers. However, it was observed that the NaOH treated fibers had higher mechanical properties compared to raw untreated fibers.

Figure 25 summarizes the different processes used to extract date palm fibers from the four sources. The figure shows ranges of the physical and mechanical properties of the extracted fibers. The sources of the values in Fig. 25 were collected from Tables 3 and 6.

Table 6 Comparison between mechanical properties of date palm fibers from different parts using different treatment techniques

Date palm part	Tensile strength (MPa)	Young's modulus (GPa)	Tensile strain (%)	Treatment technique	Notes	References
Midribs	11.4	–	–	Untreated		Ghulman et al. (2017)
	116–208	**10–30**	–	Untreated	Wall	Abdel-Rahman et al. (1988)
	71–100	10–30	–	Untreated	Core	Abdel-Rahman et al. (1988)
Spadix stems	680	13–19	–	NaOH		Taha et al. (2007)
	195 ± 28.8	8.81 ± 1.5	–	NaOH		Ibrahim et al. (2017)
	117 ± 35	–	–	Untreated		Amroune et al. (2015)
	328 ± 119	11.6 ± 4.8	**3.33 ± 0.6**	NaOH		Amroune et al. (2015)
	850 ± 247	**150 ± 191.537**	–	NaOH		Alawar et al. (2009)
Leaflets	1246.7 ± 444.7	**26.1 ± 11.2**	–	NaOH		Tahri et al. (2016)
	135	4.6	Tensile strain = 3.6 MPa	Untreated		Al-Sulaiman (2002)
	309	11.32	2.7	Retting in water		Rao and Rao (2007)
	32.43 ± 2.23	6.48 ± 0.89	4.33 ± 0.41	Untreated		Mohanty et al. (2014)
	33.33 ± 3.49	9.7 ± 1.26	5.03 ± 0.75	NaOH		Mohanty et al. (2014)
	70.72 ± 5.64	16.34 ± 1.72	**5.84 ± 0.89**	Acrylic acid		Mohanty et al. (2014)
	225	5.2	–	Untreated		Al-Sulaiman (2000)
	80	5.5	–	NaOH		AlMaadeed et al. (2013)
Mesh	215.8 ± 80	5.1 ± 1.3	–	NaOH		Tahri et al. (2016)
	459	1.91	**24**	Retting in water		Rao and Rao (2007)
	233 ± 27.1	**7.15 ± 2.0**	10.3 ± 1.57	Untreated		Abdal-hay et al. (2012)
	366 ± 36.4	5.45 ± 1.4	12.8 ± 2.4	NaOH		Abdal-hay et al. (2012)
	450	2.75	–	NaOH		Shalwan and Yousif (2014)
	310	11	–	NaOH		Elbadry (2014)
	400	–	–	NaOH		Alsaeed et al. (2013)
	5359	0.1782	11.4	Untreated		Taha et al. (2006)
	7073	0.2626	14.34	NaOH		Taha et al. (2006)
	4431	0.2047	16.48	$NaC_{12}H_{25}SO_4$		Taha et al. (2006)
	5244	0.1806	10.31	CCl_4		Taha et al. (2006)
	4462	0.2268	14.66	Toluene/methanol/acetone		Taha et al. (2006)

Thermal properties

It was observed that chemically extracted fibers had higher thermal stability than mechanically extracted fibers. This could be due to the fact that the chemical treatment helped in the removal of hemicellulose and other materials that degrade at lower temperature (Elbadry 2014).

Thermogravimetric analysis (TGA)

The TGA curves of date palm fibers were similar to the TGA curves of other natural fibers (Ali and

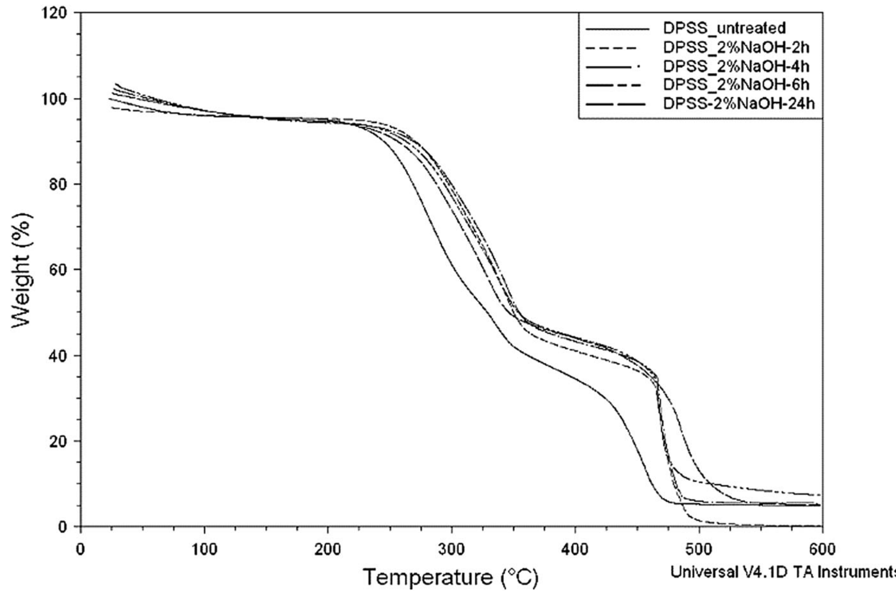


Fig. 26 TGA curves of date palm spadix stems treated with 2% NaOH solution at different durations (Taha et al. 2007)

Table 7 Decomposition temperature of date palm fibers' constituent

Date palm parts	Hemicellulose decomposition temperature (°C)	Lignin decomposition temperature (°C)	Cellulose decomposition temperature (°C)	Treatment type	References
Midrib	260–340	300–500	320–380	NaOH	Nasser et al. (2016)
Spadix stem	240	430–470	240–350	NaOH	Taha et al. (2007)
Leaflets	195–400	400–469	195–400	Mechanical	Dehghani et al. (2013)
	302–304	367–369	367–369	Mechanical	Neher et al. (2016)
Mesh	225–300	Over 350	300–350	Chemical	Taha et al. (2006)

Alabdulkarem 2017). The degradation of fibers followed three stages were the fibers lose materials like moisture; then hemicellulose and cellulose degrade and the fibers lose most of their mass. Heavy materials like lignin are last to degrade (Taha et al. 2006, 2007; Ali and Alabdulkarem 2017). Figure 26 show a typical TGA curve of date palm fibers. Table 7 summarizes the decomposition of date palm fibers found in the literature.

Differential scanning calorimetry (DSC) analysis

The DSC curves and tests show the changes that occur to the fibers when the temperature increases. Ali et al. analyzed the DSC curve of date palm mesh fibers, which is shown in Fig. 27, and found that the endothermic reaction that starts between 243–382 °C and has a peak of 369 °C indicated that the melting point of mesh fibers is at 369 °C since this point is defined as the largest endotherm. Moreover, the endothermic 369 °C temperature corresponded to the higher mass loss of nearly 52% (Ali and Alabdulkarem 2017).

Thermal conductivity

Date palm fibers were used as composites filler to reduce their thermal conductivity and reinforce them.

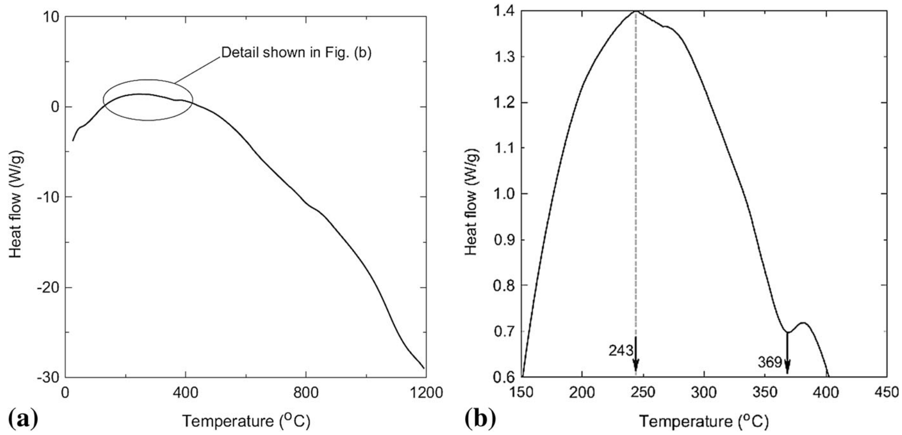


Fig. 27 Differential scanning calorimetry (DSC) thermogram of mesh fibers **a** a whole range of temperature and **b** magnified curve showing the endothermic transition between 243 and 382 °C (Ali and Alabdulkarem 2017)

The potential of using date palm reinforced composites as insulating material was studied by many researchers and they found that increasing the midribs fiber weight content in case of reinforcing mortar has increased its insulating capacity (Benmansour et al. 2014).

On the other hand, Al-Sulaiman reported that the main factors that affect the thermal insulation of date palm reinforced composites were the resin type, the fiber-to-resin ratio, and, the curing pressure. Moreover, he found that the size and orientation of leaflet fibers inside the matrix had no effect on the thermal conductivity and these results were similar to those of Masri et al. (Al-Sulaiman 2002; Masri et al. 2018). However, Zadeh et al. reported that the addition of date palm leaflet fibers has reduced the thermal conductivity of the composite when compared with the neat polymer; they attributed this reduction in the thermal conductivity to the fact that date palm fibers have low thermal conductivity which is equal to 0.087 W/mK as measured by Agoudjil et al. (2011) (Zadeh et al. 2017). Figure 28 shows comparison between thermal conductivity coefficients of some natural fibers (Al-Oqla and Salit 2017).

As for mesh fibers, Ali et al. reported that the thermal conductivity coefficient of date palm mesh fibers is density and temperature dependent and the coefficient value ranges between 0.475 and 0.0697 W/mK (Ali and Alabdulkarem 2017). Boukhattem et al. and Boumhaout et al. reposted that the addition of date palm fibers to mortar increased its thermal insulation

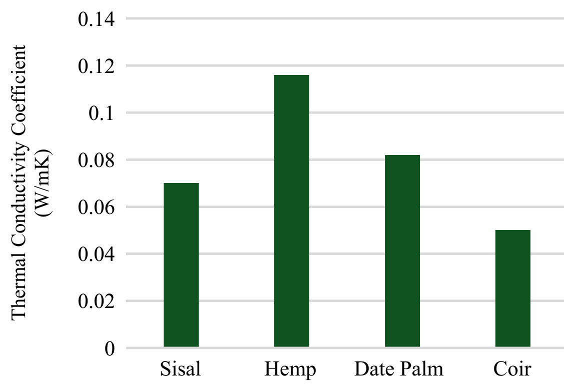


Fig. 28 Thermal conductivity coefficient values in W/mK of some natural fibers (Al-Oqla and Salit 2017)

capacity by decreasing its thermal conductivity by 70% (Boukhattem et al. 2017; Boumhaout et al. 2017).

Sound absorption properties

The sound absorption property of date palm fibers was studies by Belakroum et al. in 2017. They investigated the properties of date palm fibers extracted from the midribs and the mesh. Starch composites reinforced with date palm fibers were tested for their insulating properties and acoustic absorption coefficient. The results showed that date palm fibers enhanced the sound absorption property of the composites. From the measurements of the Moisture Buffer Value (MBV), the 50% trunk fibers composite had an average MBV of 3.73 g/(m^2 %RH). As for the samples reinforced with midribs fibers, the greatest MBV measured was 2.58 g/(m^2 %RH) (Belakroum et al. 2017).

A detailed analysis of the results that were presented in the literature could be found in the master's thesis titled "Investigating the Effect of the Chemical Treatment on the Properties of a Novel Microfibrillated Long Date Palm Fibers", where it contains a thorough critical literature review (Elseify et al. 2018).

Applications of date palm fibers

Traditional applications

Various parts of date palm were used in many applications in the past and they are still being used. However, the use of date palm fibers was limited to few applications. For instance, leaflets are shredded into coarse fibers and used as fiberfill in cushions, whereas, the fibrous mesh surrounding the trunk is usually opened and spun into cords, as shown in Fig. 29.

Novel applications

DPF have been investigated for many potential applications in the literature. Examples of these applications are papermaking, particleboards fabrication, reinforcement of gypsum, asphalt, and, cement, in addition to insulating panels, and most importantly as a reinforcement of polymeric composites. Date palm fibers were used as reinforcement to many polymer matrices. Table 8 shows the different composites reinforced with date palm fibers extracted from different date palm parts. One of the most important applications is the use of date palm reinforced composites in automotive industry since it shows a great potential in replacing other natural fibers (Al-Oqla and Sapuan 2014). Moreover, the table shows the composite production techniques in addition to the fibers' extraction methods. Also Table 9 shows investigated applications of date palm fibers other than composite reinforcement.

Fig. 29 Handmade cord made of spun date palm mesh (Contributors 2014)

In general, the reinforcement efficiency depends on the stress transfer between the matrix and the fibers. The stress transferring depends not only on the strength of fibers but also on their length. There is critical length called the critical stress transfer length; below which the fiber is regarded as an inclusion rather than a reinforcement; hence, reducing the strength of the composite. Moreover, the MFA of fibers inside the composite affects the overall strength of the composites. The smaller the MFA the more load the fiber could carry, and this is because the fibers inclination won't allow the fibers to carry the applied load fully since the load will have two components in the vertical and horizontal directions. However, larger MFA indicated higher ductility (Hakeem et al. 2014; Salit et al. 2015).

The addition of date palm fibers to cement caused amelioration of the properties of strength where the toughness was improved when fiber weight fraction was increased and long fibers were used (Kriker et al. 2005, 2008). Moreover, mesh fibers of date palm were observed to improve density and ductility of mortar (Boumhaout et al. 2017). Additionally, in a study made by Nasser et al. reported that addition of treated date palm fibers to wood and cement mixture improved their mechanical properties (Nasser and Al-Mefarrej 2011). Chaib et al. and Mokhtari et al. found that maintaining the weight fraction of mesh date palm fibers significantly reduced the thermal conductivity coefficient of the produced concrete wood (Chaib et al. 2015; Mokhtari et al. 2015). However, there was no consencus on the previously mentioned findings; Abdel-Rahman et al.'s results showed that date palm fibers didn't have significant effect on concrete as reinforcement (Abdel-Rahman et al. 1988), while Tioua et al. showed that decreasing

Table 8 List of different matrices reinforced with date palm fibers

Matrix used	Production technique	Date palm part	Fibers extraction technique	References
Epoxy	Mixing in a mold then applying pressure	Leaflets	Mechanical extraction	Sbiai et al. (2008)
	Mixing in a mold	Mesh	Mechanical extraction	Abdal-hay et al. (2012)
	–	Mesh	Mechanical extraction	Alajmi and Shalwan (2015)
	–	Mesh	NaOH	Shalwan and Yousif (2014)
	Mixing then pouring over fibers	Mesh	NaOH	Alsaeed et al. (2013)
	Laid by hand in a mold then mixed with the epoxy	Leaflets	–	Mahdi et al. (2015)
Starch based	Emulsion matrix poured over fibers then pressed	Spadix stems	NaOH	Ibrahim et al. (2014)
	Emulsion matrix mixed with fibers	Spadix stems	NaOH	Ibrahim et al. (2017)
	Mixed then pressed	Mesh	Water separation	Ali and Alabdulkarem (2017)
	–	Mesh	NaOH	Saleh et al. (2017)
	–	Midribs–mesh	–	Belakroum et al. (2017)
HPDE	Extrusion of fibers and matrix mixture into granules then hot pressed	Midribs–trunk	Glacial acid and hydrogen peroxide	Mahdavi et al. (2010)
LLDPE	Extrusion of fibers and matrix mixture into granules then hot pressed	Midribs	Mechanical extraction	Mirmehdi et al. (2014)
PP	Extrusion/Injection	Spadix stems	HCl	Alawar et al. (2008)
	Extrusion then injection Molding	Leaflets	Ethanol-toluene	Abu-Sharkh and Hamid (2004)
	Extrusion then injection molding	Mesh	NaOH	Boukettaya et al. (2018)
	Extrusion then injection molding	Leaflets	NaOH	Zadeh et al. (2017)
PU	Mixing	–	NaOH	Oushabi et al. (2017)
NR	–	Midribs	NaOH	Ladhar et al. (2017)
Polyester	Molding in aluminum mold	Mesh	NaOH	Al-Kaabi et al. (2005)
	–	Mesh	–	Wazzan (2006)
Expanded polystyrene EPS	Mixed then pressed	Leaflets	Mechanical extraction	Masri et al. (2018)
PVP	Injection molding	Leaflets	NaOH/acrylic acid	Mohanty et al. (2014)
	–	Leaflets	Acrylic acid	Mohanty (2017)
ABS	Injection molding	Leaflets	Retting	Neher et al. (2016)
PETr	Extrusion then injection molding	Leaflets	NaOH	Dehghani et al. (2013)
RLDPE/RHDPE	Extrusion then injection molding	Leaflets	NaOH	Zadeh et al. (2017)
PF/bisphenol	–	Leaflets	Mechanical extraction	Al-Sulaiman (2002)

Table 9 Investigated applications of date palm fibers in the literature

Application	Fibers source	References
Cement/concrete reinforcements	Mesh	Kriker et al. (2005, 2008), Chaib et al. (2015) Mokhtari et al. (2015), Mekhermeche et al. (2016), Boukhattem et al. (2017), Boumhaout et al. (2017), Hakkoum et al. (2017), Tioua et al. (2017)
	Spadix stems	Abdelaziz et al. (2016)
	Midribs	Nasser and Al-Mefarrej (2011)
Gypsum	Mesh	Al-Rifaie and Al-Niami (2016)
Asphalt	Bunches	Al-Otaibi et al. (2016)
Insulating panels	Leaflets	Al-Sulaiman (2003)
	Midribs	Benmansour et al. (2014)
Papermaking	Midribs	Khristova et al. (2005), Khiari et al. (2010), Abdel-Aal et al. (2015)
	Spadix stems	Hassan et al. (2014)
	Leaflets	Khristova et al. (2005)
Particleboards	Midribs	El-Morsy (1980), Iskanderani (2010), Amirou et al. (2013), Saadaoui et al. (2013), Hegazy and Ahmed (2015)
	Leaflets	Al-Sulaiman (2000), Nasser et al. (2016), Masri et al. (2018)
	Mesh	Saadaoui et al. (2013)
	Trunk	Amirou et al. (2013)

the fibers weight fraction had an inverse effect on the compressive strength of cement (Tioua et al. 2017).

On the other hand, the use of date palm fibers in the production of particleboards showed that the produced boards gave high mechanical properties if the moisture content was kept at 10% and they had excellent surface finish after machining (Al-Sulaiman 2000). Moreover, some studies reported that the MDF boards produced from date palm fibers exceeded the requirements of the EN standards (the European standards) (El-Morsy 1980; Hosseinkhani et al. 2014). However, Saadaoui et al. reported that the internal bond strength (IB) results of DPF particleboards were below the minimum required values of the Japanese Industrial Standards and the French standards (Saadaoui et al. 2013).

The addition of date palm fibers to asphalt has increased asphalt's viscosity in the temperature range 135–180 °C (Al-Otaibi et al. 2016). Moreover, date palm fibers proved to have high thermal resistance, lower thermal conductivity values, and, could be used in the production of insulation panels (Al-Sulaiman 2003; Benmansour et al. 2014). Finally, date palm fibers from midribs and spadix stems were used in papermaking, Khristova et al. found that date palm midrib fibers are similar to that of hardwood, and the best results were obtained when the midribs were pulped with alkaline sulphite-anthraquinone and alkaline sulphite-anthraquinone-methanol (Khristova et al. 2005). Moreover, Khiari et al. (2010) reported that pulps made from date palm midribs gave good quality sheets without the need of further refining operations; this gave date palm an advantage over other materials used in papermaking.

Conclusion

Date palm fibers have competitive mechanical, physical, and, thermal properties. Fibers could be extracted from many date palm parts like the midribs, spadix stems, leaflets, and, mesh. The previously mentioned four parts have different properties and chemical composition. The existence of large amount of date palm plantations made it an attractive source to produce natural fibers that have competitive properties to other natural fiber sources. Date palm fibers have high potential in replacing many other fibers in many applications like the production of sound insulating panels, thermal insulation, and, reinforcement to many materials due to their exceptional properties. However, the information found in the literature concerning date palm aren't very clear, and there are a lot of ambiguity regarding the terms used and the extraction techniques. In this review article, nearly all data in the literature was compiled to clear this confusion. Moreover, tabulated comparisons were made by comparing all the results found in the literature and analytical interpretation of data was provided. This review can help both researchers and practitioners by removing the hindrance of having to search several studies to understand the behavior of date palm fibers.

It's expected that the increasing demand for natural fibers in the reinforcement of polymer composites especially in the automotive industry will be the main driver for the commercial scale production and further development of the fibers extracted from date palm. Moreover, the increasing international trade and maritime activities will increase the demand on natural fibers for rope making in marine applications. Finally, the increased urbanization and mega projects in infrastructure and construction will increase the demand for natural fibers in geotechnical applications, such as geotextiles, as well as construction applications, such as, reinforcement of asphalt concrete and gypsum plaster. Date palm fibers are expected to play a major role in fulfilling the demand in the aforementioned applications, due to their versatility, wide availability, price advantage, and competitive technical properties.

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