An Evaluation of the Use of Midribs from Common Date Palm Cultivars Grown in Saudi Arabia for Energy Production

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This study was conducted to evaluate the suitability of date palm midribs as an alternative source for energy production. The physical properties, chemical constituents, and fuel characteristics of the midribs of five common date palm cultivars (Barhi, Khalas, Khodry, Sukkari, and Sullaj) were determined. In addition to the frond base, the midribs were divided into three distinct parts (base, middle, and top) along the frond. The results showed that both the fibre saturation point and volumetric shrinkage of the date palm midribs were much higher than those of solid wood. There were significant differences in all of the chemical constituents of the midribs between the five date palm cultivars. The date palm midribs were characterised by higher levels of extractives (19.3% for Barhi to 21.7% for Sullaj) and ash contents (3.3% for Khodry to 5.8% for Khalas). The other chemical constituents were within the ranges found for other lignocellulosic materials, including softwood and hardwood. The heating values for the midribs ranged between 17.30 MJ/kg for the Barhi cultivar and 17.89 MJ/kg for the Khodry cultivar. The higher ash content and lower density of date palm midribs makes them less desirable for energy production. It can therefore be concluded that the frond base is not suitable for energy production.

INTRODUCTION

An ever-increasing world population, in parallel with increasing concerns about the environment and climate change, has encouraged researchers to find alternative renewable biomass sources to meet the future wood demands. Fuelwood shortage is being felt at the national and global levels. To overcome this shortage and meet future demands while avoiding complete dependence on crude oil, studies have investigated the utilisation of non-wood materials, agricultural residues, fast-growing trees, low-grade wood species, and/or underutilised wood species for energy production in several countries. Recently, global interest in renewable energy sources, especially energy from biomass, has grown significantly. There have been continuous efforts to find new renewable resources as alternatives to wood harvested from natural forests for energy production. A wide variety of these materials have been investigated, including tobacco stems (Pesevski *et al.* 2010), rice waste (Salleh *et al.* 2011), common reed (Kitzler *et al.* 2012), and vine prunings (Nasser *et al.* 2014).

The kingdom of Saudi Arabia is considered one of the pioneer countries in date palm cultivation and date production. The annual production of dates is estimated at greater than 970 thousand tons, produced from more than 23 million date palm trees spread throughout different regions of the country (Al-Fuhaid *et al.* 2006). Each region is characterised by certain date palm cultivars. Although there are more than 400 date cultivars, approximately 60 cultivars are used commercially (Al-Fuhaid *et al.* 2006).

Chemical composition, heating value and density are the most important factors affecting the quality of a raw material for fuelwood and energy production. Wang *et al.* (1981) defined the heating value (MJ/kg oven-dry basis) as a measurement tool for characterization of the basic thermo-chemical value of bio-based material. It is normally used to make a comparison among different types of fuels and ranges from 17 and 22 MJ/kg based on oven-dried wood (Fengel and Wegener 1993). The chemical composition of any lignocellulosic material, including wood and the date palm midrib, has an unavoidable impact on the processing and properties of the resulting wood products in addition to profoundly influencing the utilisation of that material by the wood industry; for example, in pulp and paper (Khiari *et al.* 2011), composite products (Nasser 2012), or chemical feedstocks or as an energy source (Nasser *et al.* 2014). Chemical composition is an important technological factor to assessment the suitability of a certain type of lignocellulosic material for energy production (Wang *et al.* 1981; Nasser and Aref 2014). Woody material is composed of three main components of substances cellulose, hemicellulose, and lignin. In addition, it contains varying amounts of secondary components including extractives and ash. Higher extractives and/or lignin contents often contribute to a high heating value (Senelwa and Sims 1999; Nasser and Aref 2014), which may be attributed to their higher heating value of 23.26 to 25.59 MJ kg^{-1} compared to cellulose and hemicellulose, which both have a heating value of 18.61 MJ kg^{-1} (Baker 1983). Ash is considered as an undesirable material in most wood industries, especially for energy production (Kataki and Konwer 2002; Nasser and Aref 2014). The heating value of the woody materials is determined primarily by the difference in their chemical constituents (Kataki and Konwer 2002; Nasser and Aref 2014). The specific gravity of wood is one of the most important physical properties because of its direct or indirect relationship with many properties, which largely determine the suitability of these materials in the wood industry such as wood pulping, paper making, composite panel manufacture, and charcoal production. Denser species are preferable for fuel because of their high energy content per unit volume and slow burning rates (Kataki and Konwer 2002; Nasser and Aref 2014).

The date palm (*Phoenix dactylifera* L.) is an important element of the flora in all Arab countries (El-Mously 1997) and plays a pivotal role in economic, social, and cultural life in the Arab region. Dates were the most appropriate food supply for invading armies in the vast deserts of the Arabian Peninsula. Date palm trees have resisted the harsh climatic and environmental conditions of the area and shown generous yields, while no other type of tree has been as successful under the same conditions (Al-Fuhaid 2006).

A massive quantity of biomass results annually from the seasonal pruning of the date palm population, which is an essential agricultural practice. In a study by El-Juhany (2001), an average of 35 kg of palm residues per tree was found to be generated annually. Accordingly, the annual wasted date palm biomass in the form of residues from the

seasonal trimming of the palm tree population in Saudi Arabia is estimated to be approximately one million metric tons. Most of these residues are burnt in developing countries, whereas in developed countries, they are used to produce wood composites, such as particleboard and medium density fibreboard.

Every part of the date palm tree is utilised effectively, starting from the date fruit, including the branches, fronds, and fibres. For many years humans have obtained food, cover and building materials, fuel, and a source of warmth in the winter from the date palm tree (Al-Fuhaid 2006). Date palm residues have been used as a source of raw materials for the wood industry for the production of pulp and paper (Khiari *et al.* 2011), particleboard (Hegazy and Aref 2010), wood-plastic composites (Aref *et al.* 2013), wood-cement composites (Nasser and Al-Mefarrej 2011), and lumber-like products (El-Mously 1997). Date palm residues have also been considered as an available source for wood industries in Saudi Arabia (Nasser and Al-Mefarrej 2011; Hegazy and Aref 2010). El May *et al*. (2012) measured the gaseous and particulate pollutants during combustion of date palm wastes for energy recovery. However, they used date palm residues collected from different varieties without studying the differences between them. Similarly, Eissa and Alghannam (2013) investigated the quality of briquettes produced from date palm residues without identifying the date palm cultivar. The pyrolysis characteristics of the seeds from five date palm cultivars were reported by Babiker *et al*. (2013).

While it is important to investigate the variability among these date palm cultivars, no previous studies have been performed. Therefore, the objective of the current study was to evaluate the suitability of date palm midribs as an alternative source for energy production. In addition, this study aimed to evaluate the variations in the fuel characteristics, physical properties, and chemical constituents of the frond midribs between date palm cultivars and between different portions of the palm frond.

EXPERIMENTAL

Materials

Three healthy, 10- to 15-year-old palms showing uniform growth were selected from each of five date palm (*Phoenix dactylifera* L.) cultivars (Barhi, Khalas, Khodry, Sukkari, and Sullaj) (Table 1).

Table 1. Growth and Frond Characteristics of the Five Date Palm Cultivars

Date palm Cultivar	Trunk diameter (cm)	Palm height (m)	Frond length (cm)	Frond weight (g)		Weight* allocation (%)	
				Green	Oven-dry	Leaflet	Midrib
Barhi	71.9 ± 7.3	6.03 ± 0.2	438.3 ± 18	396.7 ± 46	118.4 ± 7	42.95	57.05
Khodry	55.7 ± 5.6	5.47 ± 0.4	360.0 ± 26	250.0 ± 10	95.9 ± 9	53.28	46.72
Khalas	52.7 ± 1.6	4.70 ± 0.3	406.7 ± 31	351.7 ± 13	128.3 ± 5	48.38	51.62
Sukkari	59.7 ± 3.9	5.85 ± 0.1	370.0 ± 22	296.7 ± 18	103.0 ± 4	55.17	44.83
Sullaj	57.4 ± 6.0	5.79 ± 0.3	446.7 ± 14	336.7 ± 35	122.6 ± 11	43.92	56.08
$LSD_{0.05}$	NS	0.49	41.7	48.0	13.5	NS	NS

Each value is an average for 3 date palm trees and 3 fronds per tree ± standard deviation
* Weight allocation is a percentage of components (leaflet or midrib) to the total oven-dry weight.
The $LSD_{0.05}$ is the least significant difference at the 0.05 level of probability

All palms were grown at the experimental station for Research and Agriculture of King Saud University, 50 km from Deyrab, Riyadh, Saudi Arabia. The site presents the following characteristics: 24° 6' N latitude, 46° 5' E longitude; temperatures ranging between 10 °C in winter and 41 °C in summer; 50 mm annual rainfall; and a calcareous soil. All trees were subjected to the same management and culture practices. During the seasonal pruning of date palm trees in December 2012, three date palm fronds (rachis) were randomly selected from the pruning residues. For characterization the studied date palm trees, the morphological characteristics of the studied palms including palm height, trunk diameter, leaf length and leaf weight are listed in Table 1.

Each midrib was divided into three zones along the frond (base, middle, and top). The lignocellulosic materials used in the current study were the frond base (BB), basal (B), middle (M), and top (T) portions, according to El-Mously (1997) as shown in Fig. 1. The materials were air dried, reduced to small pieces, ground into meal, and passed through a screen. Particles passing through a 40-mesh screen and retained on a 60-mesh screen were subjected to chemical analysis and determination of heating values.
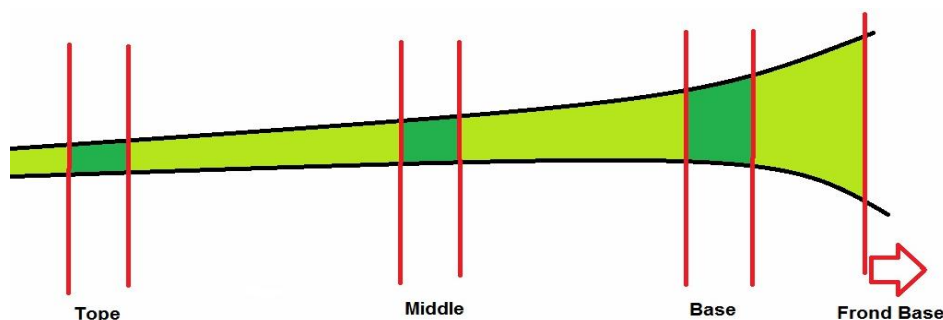

Fig. 1. Schematic representation of the four zones along the frond of date palm midrib

Methods

Physical properties determination

For the different parts of the date palms (the frond base and three zones of the midrib), the basic specific gravity (SG), fibre saturation point (FSP), and maximum moisture content (MMC) were determined using the following formulas,

$$SG = W_o/V_g \tag{1}$$

$$MMC, \% = (1.5\text{-}SG)/(1.5 \times SG) \tag{2}$$

$$FSP (\%) = TVS/SG \times 100 \tag{3}$$

where W_o is the oven-dried weight, V_g is the green volume, TVS is total volumetric shrinkage, and 1.5 is the specific gravity of the cell wall, which is consider to be constant for the method. The total volumetric shrinkage of the wood was calculated based on the green volume determined via water displacement and the oven-dried volume determined *via* water displacement after immersing the samples in wax (Haygreen and Bowyer 1996).

Extractives content determination

The extractives content of each material was determined according to the ASTM D1105 (ASTM D1037, 1989) in three steps of 4 h each, using a Soxhlet apparatus. The extractives content was calculated as a percentage based on the oven-dried weight basis.

Cellulose content determination

The cellulose content was calculated as a percentage of extractives-free meal as described by Nikitin (1960). Approximately one gram of extractives-free wood meal was treated in a flask with 20 mL of 3% nitric acid and 25 mL of a solution of 3% sodium hydroxide, and boiled for 30 min. The residue was filtered in a Gooch crucible (G3), washed with warm water to obtain a neutral filtrate, oven-dried, and weighed.

Hemicellulose content determination

The hemicellulose content was determined according to Rozmarin and Simionescu (1973). Approximately 1.5 g of extractives-free wood meal was treated with 100 mL of sulphuric acid (2%), then boiled for 1 h under a reflex condenser and filtered in a Gooch crucible (G2). The residue was washed with 500 mL of hot distilled water to remove the acid. The contents were dried in an oven at 105 ± 2 ℃, cooled in a desiccators, and weighed.

Ash content determination

Approximately 1 g of an oven-dried sample (40 to 60 mesh) was placed into a crucible and gradually heated, then ignited at 575 ± 25 °C in a muffle furnace for 6 h, or until all the carbon had been eliminated. The content of ash was calculated as a percentage of the residues based on the oven-dried wood meal weight according to the Chemical Analysis and Testing Task Laboratory Analytical Procedure (NREL 2005).

Heating value determination

The higher heating value (HHV) refers to the heating value determined using a calorimeter based on the oven-dried weight. A Parr model 6300 oxygen bomb calorimeter (Parr Instrument Company, U.S.A.) was used to determine the HHV of the date palm residues on a dry weight basis according to the ASTM standard (ASTM D2015, 1987). Approximately 1 g of an oven-dried ground sample (20 to 40 mesh) was pressed into pellets using a hydraulic pellet press and loaded into a Parr model 6300 oxygen bomb calorimeter. The calorimeter was calibrated using standard benzoic acid prior to analysis of the samples. No correction for nitric acid formation was included in the calculations of the heating value. For each material, nine specimens were combusted to estimate the heating value. The fuel value index (FVI) was calculated using the method of Bhatt and Todaria (1992) according to the equation: FVI = HHV*Density/ash content. Dry ash-free fuel (daf) was calculated using the equation: daf = HHV (1+ash content/100).

Statistical analysis

Analysis of variance (ANOVA) using a two-factorial experimental design under a completely randomised design (CRD) was employed to study the differences among the cultivars and the four zones along the midrib for all of the measured properties using the

SAS statistical package (SAS 2004). The least significant difference test at the 0.05 level of probability ($LSD_{0.05}$) was used to detect the differences between the means of all of the measured properties. Additionally, a correlation analysis was carried out to determine the relationships between the heating values and each of the chemical constituents of the date palm cultivars. Linear regression equations were calculated between the HHVs and each of chemical constituents of the date palm midribs. The choice of best model was based on the highest R^2 values.

RESULTS AND DISCUSSION

Physical Properties of the Date Palm Midribs

The analysis of variance showed that the differences between the date palm cultivars for all of the physical properties were highly significant. The mean values of the physical properties of the five date palm cultivars are presented in Table 2. The average maximum moisture content (MMC) varied between 284% for Sullaj and 378% for Barhi.

It can be seen from Table 2 that Sullaj presented the lowest mean values for the fibre saturation point (FSP) (138%), while the highest values were obtained for Sukkari (238%). The fibre saturation point (FSP) represents the point at which the cell wall is completely saturated with water, but no moisture is present within the cell lumen. For wood, this point varies among different native wood species, ranging between a 25 and 30% moisture content (Panshin and DeZeeuw 1980), although it can reach 35% in some wood species (Kollman and Cote 1968). It is clear from these results that the FSP of date palm midribs was equivalent to tenfold that of wood (FSP for wood ranges from 25% to 30%).

The basic specific gravity (SG) of the date palm midribs ranged from 0.24 to 0.29 for Sullaj and Khalas, respectively, with an average of 0.27. These results show that the density of date palm midribs is lower than the density of kiwi '*Actinida sinensis* Planch.' (0.50 g.cm^{-3}; Nemli *et al.* 2003), but close to that of hazelnut stalks (0.23 g.cm^{-3}; Copur *et al*. 2007). Accordingly, the date palm midrib is classified as "light" wood based on Panshin and DeZeeuw (1980), who classified woods with basic specific gravities of 0.36 or less as light, 0.36 to 0.50 as moderately light to moderately heavy, and above 0.50 as heavy. Many wood species with low densities can present low heating values when turned into charcoal or used for direct burning. These results were partially disagreement with those of Hindi *et al.* (2010), who found that the SG of *Phoenix dactylifera* was 0.37, without identifying the date palm cultivar.

Table 2. Physical Characteristics of the Midribs of the Five Date Palm Cultivars

Date palm cultivar	MMC (%)	Specific gravity^2	FSP (%)
Barhi	378.0 ± 67	0.248 ± 0.04	200.4 ± 20
Khodry	303.0 ± 40	0.280 ± 0.03	183.0 ± 22
Khalas	290.6 ± 59	0.293 ± 0.05	189.5 ± 37
Sukkari	357.3 ± 58	0.291 ± 0.03	238.0 ± 49
Sullaj	283.8 ± 25	0.236 ± 0.02	138.0 ± 25
$LSD_{0.05}$	9.2	0.005	10.3

Each value is an average for 36 specimens ± standard deviation.
MMC: maximum moisture content; FSP: fibre saturation point

[2]Based on the oven-dried weight and green volume
The $LSD_{0.05}$ is the least significant difference at the 0.05 level of probability

Chemical Analysis of the Date Palm Midribs

The statistical analysis showed that all of the chemical constituents of the date palm midribs differed significantly between the five date palm cultivars. The chemical characteristics of the midrib fronds from the five date palm cultivars are shown in Table 3. It can be clearly seen that the date palm midrib presents a higher total extractives content (TEC) and ash content than common wood species. The TEC ranged from 19% for the Khodry cultivar to 22% for the Sullaj cultivar. The higher extractives content may be attributed to their open anatomical structure, which is accessible to the chemicals.

The ash content ranged between 3.3% and 5.9%, for the Khodry and Khalas cultivars, respectively. These values are higher than those observed in most softwood and hardwoods, which do not exceed 1% in most species (Haygreen and Bowyer 1996) but can reach 5% in some tropical species. However, Hindi *et al.* (2010) reported higher ash content in the date palm rachis (12.3%) compared to other wood species. However, the date palm midrib presents cellulose, hemicellulose, and lignin contents that are similar to those found in other wood species, ranging from 42 to 46%, 25 to 30%, and 26 to 31% for the three chemical constituents, respectively. These values are close to the values obtained by Hindi *et al.* (2010) and Nasser and Al-Mefarrej (2011). In general, these results are in agreement with previously published studies in non-identified date palm cultivars (Hindi *et al.* 2010; Aref *et al.* 2013).

Table 3. Midrib Chemical Compositions (%) of the Five Date Palm Cultivars

Date palm cultivar	Total extractives content[1]	Cellulose content[2]	Hemicellulose content[2]	Lignin content[2]	Ash content[1]
Barhi	19.34 ± 3.6	44.14 ± 2.1	29.93 ± 1.6	25.93 ± 2.8	4.43 ± 1.4
Khodry	19.31 ± 1.5	45.74 ± 1.7	24.90 ± 2.0	29.37 ± 2.1	3.31 ± 1.2
Khalas	20.27 ± 2.0	44.91 ± 3.8	29.27 ± 3.1	25.82 ± 3.4	5.85 ± 3.2
Sukkari	21.18 ± 2.7	41.63 ± 1.4	28.31 ± 2.4	30.07 ± 2.5	5.14 ± 1.8
Sullaj	21.68 ± 2.6	42.93 ± 2.5	26.98 ± 1.2	30.09 ± 1.8	4.30 ± 1.7
$LSD_{0.05}$	**0.54**	**0.69**	**1.28**	**1.05**	**0.18**
Hardwood[3]	**2-6**	**45-50**	**15-35**	**23-30**	**0.2-0.5**
Softwood[3]	**2-8**	**45-50**	**20-32**	**25-34**	**0.2-0.5**

Each value is an average for 24 specimens ± standard deviation.
[1]As a percentage of the oven-dried weight
[2]As a percentage of the free-extractives oven-dried weight
[3]Data from Fengel and Wengener (1993)
The $LSD_{0.05}$ is the least significant difference at the 0.05 level of probability

The statistical analysis showed significant differences (P < 0.01) in all of the chemical constituents between the four positions along the frond. The chemical compositions of the date palm midribs of these four zones are presented in Table 4. The results showed that the lignin content increased moving along the frond from the base to the top, ranging from 24% to 30%. The inverse trend was recorded for the ash content, where the values decreased from the frond base to the top part of the midrib along the frond, ranging from 7.6% to 3.4%, respectively. However, no trends were observed for the other three chemical constituents (cellulose, and hemicellulose contents) and for TEC (Table 4). Although no results are available in the literature for comparison with our data, these results are partially in agreement with the findings of Bukhaev and Zaki (1983).

Generally, with exception of the frond base, it can be stated that the chemical composition of date palm midrib in the three zones along the palm frond are similar to those found in other lignocellulosic materials, including common wood. However, these zones are characterised by higher TEC and ash content. It can be concluded that all parts of the midrib frond, except the frond base are not suitable for energy production, due to its higher contents of ash and its lower specific gravity resulting in a decrease in the fuelwood value index (FVI).

Table 4. Chemical Compositions of the Date Palm Midribs at Different Positions Along the Frond

Height along frond	TEC	Cellulose content	Hemicellulose content	Lignin content	Ash content
Frond base	18.04 ± 2.9	40.74 ± 1.9	33.84 ± 2.7	25.45 ± 2.6	7.64 ± 2.0
Midrib-base	23.77 ± 3.0	44.92 ± 2.0	26.77 ± 2.1	28.30 ± 2.8	4.02 ± 0.8
Midrib-middle	18.92 ± 2.0	46.14 ± 2.4	24.59 ± 2.0	29.27 ± 3.3	3.40 ± 0.6
Midrib-top	20.68 ± 1.7	43.71 ± 2.3	26.30 ± 2.9	29.99 ± 2.5	3.37 ± 0.4
$LSD_{0.05}$	0.48	0.62	1.15	0.94	0.17

Each value is an average for 45 specimens ± standard deviation.
TEC is total extractives content.
The $LSD_{0.05}$ is the least significant difference at the 0.05 level of probability

Figure 2 shows the ash contents of the midribs from the five date palm cultivars at different positions along the frond. It can be seen that the five cultivars show the same trend of ash content variation between the four positions along the frond. The lowest values were obtained for the Khodry cultivar, while the other three cultivars presented higher values that were close to each other. For each studied palm cultivar, the differences were significant between the frond base and each of the three positions along the frond. The frond base exhibited the highest ash content compared with the other positions along the frond.
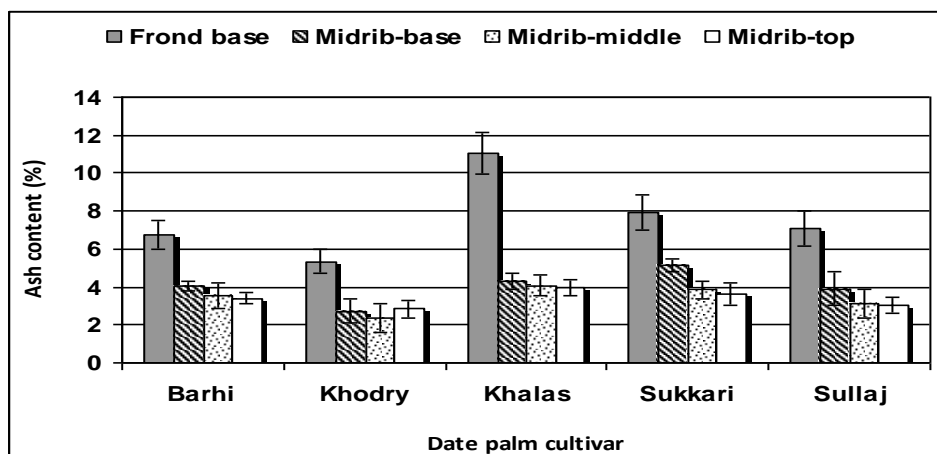

Fig. 2. Ash contents of the midribs of the five palm cultivars at four positions along the frond

Fuel Characteristics of the Date Palm Midribs

The analysis of variance revealed significant differences between the five date palm cultivars and between the different positions along the frond in terms of higher heating values (HHVs). The average values of the fuelwood characteristics for the

different date palm cultivars are presented in Table 5. It can be seen that the HHVs of the five date palm cultivars ranged from 17.3 MJ/kg (Barhi) to 17.9 MJ/kg (Sukkari). On the other hand, the HHV on an ash-free dry weight basis (daf) ranged from 18 MJ/kg (Khodry) to 18.9 MJ/kg (Khalas).

In general, the results shown in Table 5 revealed that the date palm midribs showed lower FVI values compared with the published values for different wood species, which can be attributed to the higher ash contents found in the five palm cultivars and the lower specific gravity. Similar results were obtained by Nasser *et al*. (2014) for vine prunings (FVI ranging from 225 to 508). On the other hand, Kataki and Konwer (2002) reported a wide range of FVI values, from 369 for *Litsea polyantha* to 2089 for *Acacia nilotica*, which presented ash contents ranging from 3.6 to 0.9%, respectively. This means that the ash content is the most important variable adversely affecting FVI values.

The HHVs for the date palm midribs were found to be lower than those of some well-known biomass fuels reported in the literature, such as common reed (18.9 MJ/kg; Komulainen *et al.* 2008), *C. procera* (19.5 MJ/kg; Hindi 2013), and vine prunings (18.7 to 19.2 MJ/kg; Nasser *et al.* 2014), but close to the heating values of corncobs (17 MJ/kg; Demirbas 2003) and tobacco stems (17.8 MJ/kg; Pesevski *et al.* 2010). In view of the obtained heating values and compared to other biomass fuels, the results indicated that these residues can be considered as a source of energy production. Unfortunately, the high ash contents of all parts of the date palm midrib, especially the frond base, makes them less desirable for use as a source of fuelwood because the ash content has a negative effect on the fuelwood characteristics (Goel and Behl 1996; Nasser *et al*. 2014).

Table 5. Fuel Characteristics of the Midribs of the Five Date Palm Cultivars

| Date palm cultivar | Heating value (MJ/kg) | | Fuel value index |
	HHV	Dry free-ash (daf)	(FVI)
Barhi	17.30 ± 0.68	18.07	175.73
Khodry	17.42 ± 0.51	18.00	305.77
Khalas	17.89 ± 0.53	18.94	194.19
Sukkari	17.88 ± 0.68	18.80	203.15
Sullaj	17.78 ± 0.62	18.54	203.43
LSD$_{0.05}$	**0.16**	**-**	**16.03**

Each value is an average for 36 specimens ± standard deviation.
The LSD$_{0.05}$ is the least significant difference at the 0.05 level of probability

According to ANOVA, there were significant differences ($P < 0.01$) in the heating values of the midribs between the four positions along the palm fronds. It can be noted from Table 6 that the HHV increased significantly from 16.8 MJ/kg at the frond base to 18.2 MJ/kg at the top of the midrib (top zone).

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Table 6. Fuel Characteristics of the Midribs at Positions along the Palm Frond

Height along frond	Heating value (MJ/kg)		Fuel value index (FVI)
	HHV	Dry free-ash (daf)	
Frond base	16.75 ± 0.27	18.03	97.12
Midrib-base	17.70 ± 0.46	18.41	229.8
Midrib-middle	18.02 ± 0.28	18.63	335.5
Midrib-top	18.19 ± 0.24	18.75	319.7
LSD$_{0.05}$	**0.14**	**-**	**-**

Each value is an average for 45 specimens ± standard deviation.
The LSD$_{0.05}$ is the least significant difference at the 0.05 level of probability

Due to the decrease in the content of ash with increasing density and HHVs in the midrib from the base to the top, the FVI was increased in the same manner, from 97 to 336 (Table 6). The results indicated that among the four positions along the frond, the frond base shows the lowest values for fuel characteristics, including heating values, and the FVI, making it less desirable for use as fuelwood.

Figure 3 shows the heating values on a dry weight basis for the midribs from the five date palm cultivars at different positions along the frond. It is clear that for each cultivar and between the four positions along the frond, there is a single trend in the variation of heating values. For each cultivar, the heating values generally increased along the frond from the base to the top. The lowest values were recorded at the frond base, and the highest were obtained at the top of the midrib. This may be attributed to increasing the lignin and extractives content from base to top along the frond height as well as to decrease the ash content in the same direction as seen from Table 4. The Barhi and Khalas cultivars exhibited the lowest heating values compared with the other cultivars.
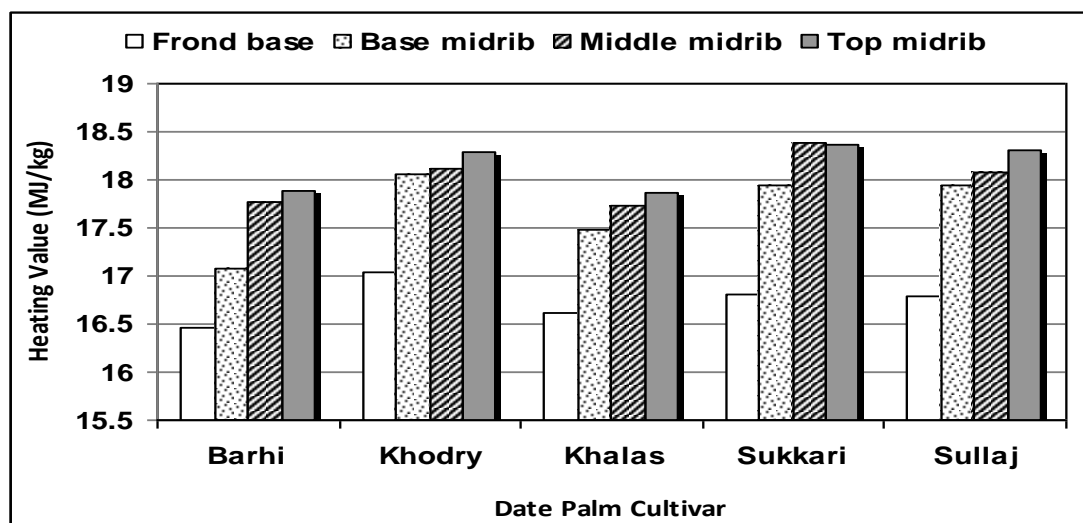

Fig. 3. Higher heating values for the midribs of the five palm cultivars at four positions along the frond

Table 7 shows the correlation coefficient matrix for the higher heating values, each of the chemical constituents and the specific gravities of the date palm midrib. All of the correlation coefficients, except those for the TEC and cellulose contents, were highly significant (P < 0.01). There were highly significant positive correlations between the

HHVs and the lignin contents ($P < 0.01$). On the other hand, negatively significant correlations were found with ash content ($P < 0.01$) and hemicellulose content ($P < 0.01$). However, the correlations with TEC and the cellulose content were positive but non-significant ($P > 0.05$). These results are in agreement with those of Kataki and Konwer (2002), Munalula and Meincken (2009), and Nasser *et al.* (2014).

Table 7. Correlation Coefficient Matrix for the Date Palm Midrib Fronds

	TEC	Cellulose	Hemicellulose	Lignin	Ash	SG
HHV	0.34[NS]	0.48[NS]	-0.80[**]	0.86[**]	-0.82[**]	0.61[**]

HHV: Higher heating value; TEC: Total extractives content; SG: Specific gravity
[NS]Not significant
[**]Correlation coefficients are significant at the 0.01 levels of probability

Linear regression equations were calculated between the higher heating values and each of the chemical constituents of date palm midribs. The choice of the best model was based on the highest R^2 values. The best reduced regression models representing the variation in the HHVs of the date palm midribs are provided in Table 8. The results indicated that the content of lignin and ash are the major factors influencing the higher heating values of the date palm midribs. The best reduced model contained the lignin content and ash content, which presented the highest R^2 value (0.79) and explained approximately 79% of the total variation in the HHVs of the date palm midribs. The simple linear equations contained one variable for the lignin content and ash content and they explained approximately 79% of the total variations in HHVs, respectively.

The increase in the heating value must have been caused by the increased extractives and lignin contents, which showed higher heating values relative to the cellulose and hemicellulose contents. The mean differences in the heating values of softwoods and hardwoods are said to be caused primarily by the difference in their lignin contents (White 1987). According to Baker (1983), cellulose and hemicellulose present a lower heating value of 18.6 MJ/kg, whereas that of lignin is higher at 23.3 to 25.6 MJ/kg.

Table 8. Best Reduced Regression Models for Representing the Variation in Higher Heating Values (HHV)

Model	N	S_{EE}	R^2
HHV= 12.77+0.17Lig[**]	20	0.87	0.64[**]
HHV= 18.75-0.24Ash[**]	20	0.20	0.67[**]
HHV= 15.52+0.10Lig[**] - 0.15Ash[**]	20	1.03	0.79[**]

N = number of measurements. Lig. is lignin content.
S_{EE} = standard error of the estimates
R^2 = coefficient of determination
[**]significant at the 0.01 level of probability

Ranking of the Date Palm Cultivars

According to Munalula and Meincken (2009), the hypothetical ratings of some of the data measured in the five date palm cultivars regarding fuel characteristics are presented in Table 9. Under this method, the Sukkari palm cultivar showed the most preferable order (1.2), followed by the Khalas cultivar (2.0), followed by the cultivar Khodry and Sullaj (2.4), while the cultivar Barhi showed the poorest rating (3.2).

Table 9. Ratings of the Five Date Palm Cultivars Regarding Some of the Determined Properties

Property	Date palm cultivar				
	Sukkari	Khalas	Khodry	Sullaj	Barhi
Higher heating value	1	1	3	2	4
Specific gravity	1	1	2	4	3
Ash content	1	1	4	3	2
Lignin content	1	4	2	1	3
Fuel value index	2	3	1	2	4
Rating value*	**1.2**	**2.0**	**2.4**	**2.4**	**3.2**

According to Munalula and Meincken (2009)

The overall ratings reveal that the Sukkari and Khalas palm cultivars showed the most preferable parameters, and these cultivars could be more suitable for energy production in Saudi Arabia compared with the other palm cultivars studied.

CONCLUSIONS

1. Date palm midribs were found to present higher total extractives content (19.34 to 21.68%) and ash content (3.31 to 5.85%) in comparison with softwood and hardwood.

2. Highly positive-significant correlations were found between the HHV and the lignin content and biomass/ash ratio, whereas a highly negative-significant correlations were found between the HHV and the ash content and the hemicellulose content.

3. The relatively high heating values found for the date palm midribs (17.3 to 17.9 MJ/kg) indicate that they are promising as an energy source. Unfortunately, the high ash content of all parts of the date palm midribs, especially the frond base, makes them less desirable for use as a source of fuelwood.

4. The midribs of the date palm fronds exhibited the lowest FVI values (97 to 336) compared with the values published in the literature for different wood species.

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