Chemical Analysis of Different Parts of Date Palm (Phoenix dactylifera L.) Using Ultimate, Proximate and Thermo-Gravimetric Techniques for Energy Production

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Date Submitted: 2018-11-27

Keywords: thermo-gravimatric analysis, Energy, proximate analysis, ultamiate analysis, date palm

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Citation (overall record, always the latest version): LAPSE:2018.1069
Citation (this specific file, latest version): LAPSE:2018.1069-1
Citation (this specific file, this version): LAPSE:2018.1069-1v1

DOI of Published Version: https://doi.org/10.3390/en9050374 *energies*

Article

Chemical Analysis of Different Parts of Date Palm (*Phoenix dactylifera* L.) Using Ultimate, Proximate and Thermo-Gravimetric Techniques for Energy Production

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Academic Editor: Shusheng Pang
Received: 16 March 2016; Accepted: 6 May 2016; Published: 16 May 2016

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Keywords: date palm; ultamiate analysis; proximate analysis; energy; thermo-gravimatric analysis

1. Introduction

New renewable resources including corncobs [1], tobacco stems [2], rice waste [3], common reed [4,5], vine prunings [6], and date palm midribs [7], are getting more and more popular as alternative materials to solid wood harvested from natural forests for bioenergy production. Date palm (*Phoenix dactylifera* L.), one of the most important non-wood renewable resources in the Middle East, used mainly for its fruit, fiber and as a construction material [7,8] could also be considered a raw material for energy production. The residues are used in various industries as raw materials for many applications such as lumber [9], particleboard [10–12], pulp and paper [13–15], wood-cement composites [16], wood-plastic composites [17,18], oriented strandboard [19], for the pyrolysis characteristics of the seeds [20], in briquette production [21], and for biochar production [22,23].

The Kingdom of Saudi Arabia is considered one of the pioneering countries in date palm cultivation and the annual date production is more than 970,000 tons, from the area of some 150,000 ha [24,25]. The Sukkari cultivar is an important variety cultivated in most areas of the kingdom for its high quality fruits and good economical returns to farmers. According to Agoudjil *et al.* [26], the main parts of the date palm tree are: (a) the palm trunk; (b) the mesh; (c) the leaves, frond base petiole, rachis, leaflets and spines; (d) the reproductive organs (spathes, fruit stalk, spikelets and pollen) and (e) a number of palm products obtained from the bunches (fruit bunch empty, fruits and seeds). In practice, under normal conditions, 6–10 bunches per palm are obtained and 12–15 new leaves are formed and trimmed annually.

Several factors affect the fuel properties of biomass feedstocks. Lignin and higher extractives contents contribute to a high heating value [27,28], while ash is considered as an undesirable material in wood for energy production [28,29]. Heating value and density of the raw material are also very important factors affecting the overall energy production output [13,28,30–32].

The chemical energy of a solid fuel is stored in the forms of volatiles and fixed carbon [33]. The volatiles or volatile matter content (VMC) is the portion that is driven-off as a vapor or gas by heating the fuel to 950 °C, while the remaining is known as fixed carbon (FC), excluding the ash and moisture contents. The measurement of these two forms gives what is known as a proximate analysis, which is a chemical analysis method that determines contents of VM, ash and FC. It is an excellent tool to describe and predict the heating values of a biomass [17,34–39]. In a previous work a simple equation to predict the heating values of three wood species, namely *Pinus halepensis*, *Quercus rotundifolia* and *Eucaluptus saligna* and three lignocellulosic wastes olive seeds, almond shells and wet straw from Southern Spain was established by using proximate analysis [34]. For a typical wood biomass without bark, the ash content is around 0.3% based on the findings of a past work [38]. In another study the ash content of a similar material ranged from 5% to 20% [39].

During the seasonal pruning of palms and with exception to the trunk, all secondary products are used for various purposes [9]. Substantial quantities of annual biomass therefore result from the seasonal pruning date palms, an essential agricultural practice in Saudi Arabia. An average of 35 kg of palm residues per tree is generated annually [40]. Accordingly, the annual wastes resulting from date palm biomass in Saudi Arabia are estimated to be approximately one million metric tons. In developing countries, most of date palm residues are burnt or left as landfill creating serious environmental pollution [21,26]. In developed countries, such wastes are used as raw material for the production of composite panels. Although there are a few literature studies that investigate the suitability of date palm residues for energy production [7,41], there is very little information on what parts of date palm tree are suitable for charcoal and energy production [41]. Abed *et al.* [42], tested the pyrolysis of date palm stones and stalks by thermogravimetric analysis and reported that these kinds of palm by-products constituted a significant alternative to implement a potential new renewable energy source. Babiker *et al.* [20] performed a thermogravimetric analysis of date palm stones (DPS) of six cultivars and they revealed that DPS contain much volatile compounds. El May *et al.* [41] measured the gaseous and particulate matter obtained during the combustion of four parts of date palm wastes and their energy recovery and they found that DPS was the most convenient date palm waste for energy recovery. The objective of this study is to investigate energy production from different parts of the date palm employing proximate analyses so that such an underutilized waste might be converted into a value-added product.

2. Materials and Methods

2.1. Preparation of Date Palm Samples

Five defect-free Sukkari cultivar date palms (*Phoenix dactylifera* L.) with ages ranging from 10- to 15-years, were used for the experiments [7]. All palms were harvested at the Experimental Station for Research and Agriculture of King Saud University, approximately 50 km from Deyrab (Riyadh, Saudi Arabia). The site has 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.

During the seasonal pruning of date palm trees in December 2013, different date palm parts including trunk (PT), palm frond base (PFB), palm frond midrib (PFM), palm leaflets (PL), palm coir (PC), spadix stem or fruit stalk (FS), seeds or date palm stone (DPS), and fruit empty bunches (FEBs) were collected from each palm tree and weighed as displayed in Table 1. *Acacia tortilis* wood was used as a control sample. After air-drying, the residues were cut into small particles and ground using a Wiley mill, before the raw material was screened. Particles with a size of 20–40 mesh were used to determine the fuel characteristics, while those with a 40–60 mesh size were used for determination of the chemical and ultimate analysis of the specimens.

Table 1. Characterization of different part residues of the Sukkari date palm cultivar.

Tree	**Trunk Diameter**	**Palm Height**	**Frond Length**	**Fruit Weight ***	**Oven-Dry Weight (kg/tree)**							
No.	**(cm)**	**(m)**	**(cm)**	**(Kg/tree)**	**PFB**	**PFM**	**PL**	**PC**	**DPS**	**FS**	**FEB**	**Total**
1	63.1	5.88	385.3	125.3	5.67	14.40	8.05	1.33	18.53	7.19	0.75	55.92
2	51.3	6.15	380.9	144.6	6.48	15.89	6.65	1.65	20.88	8.06	1.02	60.63
3	71.1	7.12	345.4	116.5	6.08	13.02	6.30	2.15	16.05	6.32	0.93	50.85
4	66.6	5.97	375.0	122.3	6.89	14.89	8.14	1.84	19.19	8.53	0.76	60.24
5	68.4	6.75	363.5	132.7	6.08	15.11	7.95	1.51	20.99	7.45	1.20	60.29
Mean	**64.1**	**6.37**	**370.0**	**128.3**	**6.24**	**14.66**	**7.42**	**1.70**	**19.13**	**7.51**	**0.93**	

Each value is an average of three fronds per tree. * Oven-dry weight. PFB: palm frond base; PFM: palm frond midrib; PL: palm leaflets; PC: palm coir; FS: fruit stalk; DPS: date palm stone; FEB: fruit empty bunch.

2.2. Chemical Analysis

Total extractives of the eight different parts of date palm were determined using a Soxhlet apparatus according to ASTM D1037 [43]. The contents of cellulose, hemicelluloses, and lignin were determined using the meal free-extractive method based on the oven-dry weights for each residue, also according to the methods described in the ASTM D1037 standard method [43]. Ash contents of the samples were calculated as a percentage of the original quantity of the specimens based on oven-dry weight according to a standard method developed by National Renewable Energy Laboratory (NREL, Golden, CO, USA) [44].

2.3. Ultimate and Proximate Analyses

Ultimate analysis of the residues of the different parts of date palm (including carbon, hydrogen and nitrogen contents) was carried out using a CHN Elemental Analyzer (model 2400 Series II Perkin Elmer, Waltham, MA, USA) at 925 °C [45]. The oxygen content of the samples was calculated by difference. For proximate analysis, residues samples were oven-dried to a constant weight at a temperature of 103 ± 5 °C. Samples having 40–60 mesh particle size were used to determine the moisture content (MC), volatile matter content (VMC) and ash content, while the fixed carbon content (FCC) was calculated by difference [43].

2.4. Fuel Characteristics of the Samples

Fuel characteristics of the specimens including heating value (HV) based on dry basis (db) and dry ash-free fuel (daf) as well as fuel value index (FVI) was determined. HV of the residues of the eight parts of the Sukkari cultivar date palms were determined on a db according to the standard method described in ASTM D2015-85 [46]. Approximately one gram of oven-dried ground sample with a particle size ranging from 20 to 40 mesh was converted into pellets using a hydraulic pellet press and loaded into a model 6300 oxygen bomb calorimeter (Parr, Moline, IL, USA). Before the analysis of the samples, the calorimeter was calibrated using benzoic acid as a standard. No correction for acid formation was included in the heating value calculations. Six samples from each date palm part were combusted to estimate the heating value. The fuel value index, FVI, was calculated using a modified method of Bhatt and Todaria [47], FVI = HV × density/ash content. Dry ash-free fuel (daf) was also calculated.

2.5. Ranking of the Different Samples

To rate the eight date palm residues of Sukkari date palm cultivar, as well as the wood of *Acacia tortilis*, according to the positive and/or negative impacts on the bioenergy content and environmental impact, this property was assigned a value between 1 and 9, with 1 being the best and 9 being the worst according to Munalula and Meincken [48]. Ratings were calculated as the sum of all values in the column divided by the number of measured properties ($\Sigma/8$). This rating value refers to energy output and environmental impact.

2.6. Statistical Analysis

The analysis of variance (ANOVA) using a complete randomized design (CRD) was employed to test the differences between the eight date palm residues and *A. tortilis* in all the measured properties using the SAS statistical package [49]. Least significant difference at 5% level of probability ($LSD_{0.05}$) was used to detect the differences among the means of all the measured properties. Correlation analysis was also carried out to find out the relationship between the heating value and each of the chemical constituents and ultimate and proximate analysis of the date palm residues.

3. Results and Discussion

3.1. Chemical Composition of the Date Palm Residues

Table 2 presents the chemical composition of the eight parts of the Sukkari date palm residues compared to that of *Acacia tortilis* wood and other biomasses. Statistically, all of the chemical constituents showed significant differences from each other among the eight date palm residues. It can be clearly seen that the date palm residues presented a higher total extractives content (TEC) than common wood species, with a high variation range. The palm coir (PC) had the lowest TEC (7.8%) followed by date fruit stalks (FS, 9.8%), while palm leaflet (PL) had the highest amount of extractives (32.9%) followed by date palm stones (DPS) with about 31.5%. The higher extractives content of PL may be attributed to its open anatomical structure, which is accessible to the chemicals. These values are close to the values obtained on midribs of five date palm cultivars [7], and on some lignocellulosic residues [36], while they are lower than those reported for date palm trunk (PT) and rachis [11]. There is very little information to compare chemistry of the different parts of date palm residues, but the results found in this work are in partial agreement with previously published studies on non-identified date palm cultivars [17,50].

The cellulose content of the samples ranged from 32.8% for DPS to 47.5% for PC. It can be seen that PT, PFB, FS and DPS had lower cellulose content than typical wood species, while the other parts fall in the range of these wood species. These results are in accordance with the findings of a previous work carried out by Amirou *et al.* [11] on two date palm residues (trunk and rachis) and [7] on the midrib of five date palm cultivars. However, these values are lower than those reported for some lignocellulosic residues [36].

Except for PC and PL, the hemicelluloses content for the date palm residues were similar to those of wood and non-wood plants. The lowest values of hemicelluloses were recorded with PC and PL

(12.6% and 16.1%, respectively), while the highest values were obtained with PT, PFB and DPS (Table 2). These results agree with previously reported data [7,11,13,15,16,50].

Table 2. Chemical composition (%) *of the date palm residues of Sukkari cultivar.

Feedstock	Percentage Content of			
	Total Extractives ^{1}	**Cellulose** ^{2}	**Hemicelluloses** ^{2}	**Lignin** ^{2}
Palm Trunk (PT)	25.15 ^{B} (0.40)	39.37 ^{D} (0.71)	**30.31** ^{A} (0.69)	30.32 ^{D} (1.44)
Palm Frond Base (PFB)	24.90 ^{B} (0.41)	43.05 ^{C} (0.21)	**31.34** ^{A} (1.59)	**25.61** ^{E} (1.42)
Palm Frond Midrib (PFM)	17.45 ^{C} (1.61)	45.16 ^{B} (1.32)	28.16 ^{B} (1.47)	**26.68** ^{E} (0.69)
Palm Leaflets (PL)	**32.86** ^{A} (0.85)	**47.14** ^{A} (0.60)	16.13 ^{E} (0.15)	36.73 ^{B} (0.46)
Fruit Stalk (FS)	9.75 ^{E} (0.49)	43.05 ^{C} (1.13)	27.48 ^{B} (0.14)	29.47 ^{D} (1.05)
Fruit Empty Bunch (FEB)	13.42 ^{D} (0.92)	44.40 ^{BC} (0.90)	24.30 ^{C} (0.56)	31.30 ^{C} (1.32)
Date Palm Stone (DPS)	**31.54** ^{A} (0.50)	**32.77** ^{E} (0.17)	**30.20** ^{A} (0.50)	37.03 ^{B} (0.33)
Palm Coir (PC)	**7.78** ^{F} (1.35)	**47.50** ^{A} (0.62)	**12.64** ^{F} (0.41)	**39.86** ^{A} (0.23)
Acacia tortilis (AT)	13.82 ^{D} (0.16)	**46.92** ^{A} (0.69)	21.27 ^{D} (0.77)	31.81 ^{C} (0.56)
Hardwood ^{3}	2–6	45–50	15–35	23–30
Softwood ^{3}	2–8	45–50	20–32	25–34
Date palm Trunk and riches ^{4}	1–9	36–47	29–38	17–27
Date palm residue ^{5}	20.3	45.0	29.1	25.8
Lignocellulosic residues ^{6}	12–29	51–66	–	11–22
Six eucalyptus clones ^{7}	3–5	46–49	22–23	29–31
Midrib of six date palm cultivars ^{8}	18–24	41–46	25–34	25–30
Prunings of seven vine cultivars ^{9}	18–26	37–40	31–35	27–30

* Each value is an average for 10 specimens and the values between brackets are standard deviations. In the column, bold under line value is the highest value and bold italic value is the lowest one. Means sharing the same letters within the same column are non-significantly different at the 0.05 level of probability. ^{1} As a percentage of the oven-dried weight. ^{2} As a percentage of the free-extractives oven-dried weight. ^{3} Fengel and Wegener [31]. ^{4} Amirou *et al.* [11]. ^{5} Nasser and Al-Mefarrej [16]. ^{6} Jiménez and González [36]. ^{7} Pereira *et al.* [51]. ^{8} Nasser [7]. ^{9} Nasser *et al.* [6].

The lignin content of the samples ranged from 25.6% for PFB to 39.9% for PC. It is clear that the determined lignin contents of the DPS, PC and PL were very high when compared to that of either softwoods or hardwoods (Table 2). Other parts gave lignin values ranging from 26% to 31%, similar to those found in other wood species and non-wood plants.

Accordingly, the chemical composition of the eight date palm residues is significantly different, which may explain the differences in the fuel characteristics between them. Although no results are available in the literature for comparison with our data in this study, these results are in partial agreement with the findings of previous works [7,11,15,16,36,43].

3.2. Ultimate and Proximate Analysis of Date Palm Residues

The average proximate analysis values for the eight date palm residues are presented in Table 3. It can be seen that there is a large variation in the values of the proximate analysis results of the eight date palm residues. They had the following values: volatile matter content (VMC) ranged from 74.3% for PL to 87.5% for FBE; fixed carbon content (FCC) ranged from 10.5% for PL to 17.6% for palm trunk (PT) and the ash content ranged from 1.4% (DPS) to 15.2% (PL).

With the exception of PT, PL and FB, the VMC of the residues was greater than 82%. Most of this matter was released and burned as gases when heated during combustion process [52]. The lowest value of FCC was obtained for PL and PC without any significant differences between them and their values were less than those of *A. tortilis* wood (11.4%), while the remaining FCC values were higher than those of wood. The higher VMC of some date palm residues compared to the wood of

A. tortilis indicated that they are more reactive than wood. The low FCC obtained in some residues reflected their high VMC, and showed that the bulk of the residues are consumed in the gaseous state during combustion.

In general, ash content is an unfavorable factor that needs to be controlled during the direct combustion of wood [53]. The date palm residues were characterized by higher ash content [7,50] than those observed in common wood species which does not normally exceed 1% but can reach up to 5% in some tropical species [54], where FB and PL had the highest ash values of 9.8% and 15.2%, respectively, which is less desirable for energy production. The high ash content in PL may be due to the concentration of potassium in the actively metabolizing positions where the nutrients from the soil are fixed prior to relocation to other parts of the plant [27]. Furthermore, tropical wood species need more mineral elements for growth than other woods [53], so the high ash content in date palm residues might be attributed to the growth conditions in Saudi Arabia where the trees grow naturally in an arid region compared to the same species growing in moist regions outside the kingdom [28].

Table 3. Ultimate and proximate analyses of the Sukkari date palm residues.

Feedstock	**Ultimate Analysis** ^{1}				**Atomic Ratio** ^{2}		**Proximate Analysis** ^{1}		
	C	**H**	**N**	**O** ^{3}	**H/C**	**O/C**	**VM**	**Ash**	**FCC** ^{3}
PT	44.46 ^{d}	5.75 ^{c}	0.55 ^{c}	49.24 ^{c}	1.55 ^{cd}	0.83 ^{c}	78.53 ^{g}	3.86 ^{c}	**17.61** ^{a}
PFB	**40.48** ^{f}	***5.63*** ^{c}	0.28 ^{de}	**53.61** ^{a}	1.67 ^{a}	**0.99** ^{a}	76.56 ^{f}	9.81 ^{b}	13.63 ^{c}
PFM	45.65 ^{c}	5.95 ^{bc}	0.27 ^{de}	48.13 ^{c}	1.56 ^{c}	0.79 ^{c}	82.28 ^{e}	3.56 ^{c}	14.15 ^{bc}
PL	46.50 ^{b}	5.69 ^{c}	0.66 ^{b}	47.15 ^{d}	**1.50** ^{d}	0.90 ^{b}	**74.29** ^{h}	**15.2** ^{a}	**10.51** ^{f}
FS	44.47 ^{d}	5.97 ^{bc}	0.32 ^{d}	49.24 ^{c}	1.61 ^{b}	0.83 ^{c}	85.32 ^{c}	1.80 ^{e}	12.88 ^{d}
FEB	45.58 ^{c}	6.03 ^{b}	0.26 ^{de}	48.13 ^{c}	1.59 ^{bc}	0.79 ^{c}	**87.48** ^{a}	1.78 ^{ef}	10.75 ^{f}
DPS	**47.14** ^{ab}	**6.63** ^{a}	**0.90** ^{a}	***45.33*** ^{e}	**1.69** ^{a}	**0.72** ^{d}	83.33 ^{d}	**1.40** ^{f}	14.94 ^{b}
PC	**47.84** ^{a}	6.15 ^{b}	***0.23*** ^{e}	***45.78*** ^{e}	1.54 ^{cd}	**0.72** ^{d}	86.57 ^{b}	2.90 ^{d}	**10.53** ^{f}
Acacia tortilis	**46.70** ^{b}	**6.04** ^{b}	**0.34** ^{d}	**46.92** ^{d}	**1.59** ^{bc}	**0.79** ^{c}	**86.67** ^{b}	**1.92** ^{e}	**11.41** ^{e}
Hardwood [55] ^{4}	50.8	6.4	0.40	41.80	1.51	0.62	77.3	3.4	19.4
Softwood [55] ^{4}	52.9	6.3	0.10	39.70	1.43	0.56	77.2	1.6	22.0
LCM [34] ^{5}	42–50	5.7–6.1	0.1–1.0	41–47	-	-	75–84	0.1–8.1	14–20
Residual biomass [56] ^{6}	49–51	~6	0.1–0.6	42–45	-	-	78–84	0.6–3.7	16–20
LCR [36] ^{7}	-	-	-	-	-	-	69–88	1–6	11–25
Prosopis [57] ^{8}	-	-	-	-	-	-	77–80	1.1–1.3	11–15
Pereira *et al.* [51]	44–47	5.6–6.0	~0.1	47–51	1.5–1.6	0.7–0.9	-	-	-
Telmo *et al.* [38]	46–52	4.9–6.1	0.1–0.5	40–47	-	-	75–81	0.1–1.0	12–23
Yao *et al.* [58]	38–53	4.5–7.0	0.2–2.7	32–45	-	-	65–85	0.5–20	7–20
El May *et al.* [41]	40–51	5.6–6.4	0.2–0.7	41–46	-	-	68–74	1–15	8–18
Nasser *et al.* [6]	46–48	5.5–5.7	0.8–1.1	45–47	-	-	-	-	-
Lee *et al.* [59]	49–62	4.4–6.1	0.2–2.0	33–43	-	-	49–80	0.4–21	11–25

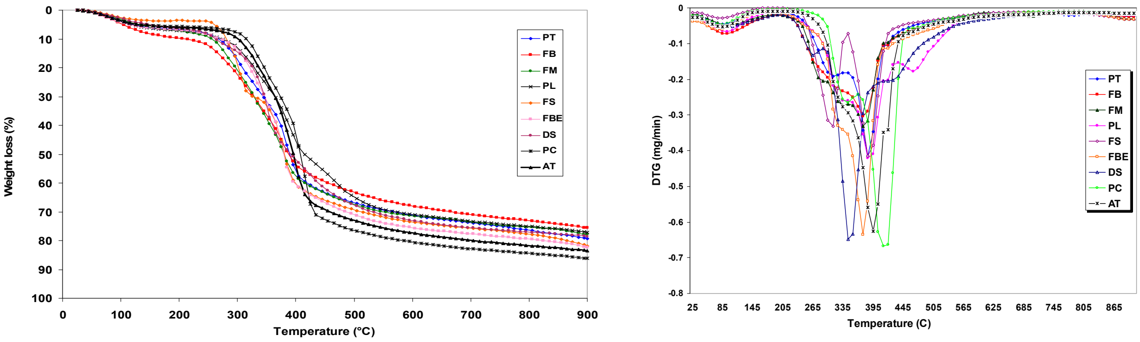
VM is volatile matter content and FCC is fixed carbon content. Means sharing the same letters within the same column are non-significantly different at 0.05 level of probability. ^{1} Percentage on a dry weight basis. ^{2} According to Pereira *et al.* [51]. ^{3} Calculated by difference. ^{4} Source: C, H, N, and O from Arola [55], while H/C and O/C ratios were calculated. ^{5} Lignocellulosic materials. ^{6} Residual biomass included olive stone, almond shell, pine wood and olive-tree prunings. ^{7} Lignocellulosic residues. ^{8} Two species of *Prosopis juliflora* and *P. pallid* grown in Kenya.

This result is in agreement with Nasser [7], who reported that all parts of the date palm midribs had high ash content, especially the PFB, which makes them less desirable for fuelwood production. Based on the FAO [60], most of the date palm residues studied here meets the standard specifications for high-quality lump charcoal which typically has an ash content of about 3%.

By comparing the obtained values of date palm residues with coal, it can be concluded that the VMC in the residues is much higher than in coals, but FCC is much lower, which resulted in an increase in the reactivity of the residues. These results are in agreement with the outcomes of several studies worldwide that reported data for many types of biomass [36–39,41,57]. They reported the following values for general biomass including wood biomass, VMC ranged from 68% to 88%, FCC is from 7% to 35% and ash content is from 0.1% to 21% (Table 3).

3.3. Thermal Properties of the Date Palm Residues

Thermo-gravimetric analysis (TGA) shows the thermal behavior of a sample, which is an important parameter in the design of reactors for the pyrolysis of materials [61]. The TGA and derivative thermogravimetric (DTG) curves of the date palm residues are shown in Figure 1a,b. It can be said that except for PL, the thermal decomposition was complete below 500 °C. For each residue, there are one or two distinct peaks corresponding to the decomposition of hemicellulose and cellulose [62]. The decomposition of lignin took place over a wide range of temperatures up to 900 °C. The DTG curves revealed that the maximum weight loss rate was took place from 228 °C to 512 °C depending on the residue. In this temperature range, the hemicelluloses and cellulose were decomposed. The hemicellulose, cellulose and lignin decomposed in temperature ranges of 260–340 °C, 320–380 °C and 300–580 °C, respectively. During the decomposition of the three components, they are seen to be overlapped with each other and can therefore be considered as pseudo-components.



(**a**) (**b**)

Figure 1. (**a**) TGA curves of the eight date palm residues and *A. tortilis* at heating rate of 10 °C/min; (**b**) DTG curves of the eight date palm residues and *A. tortilis* at heating rate of 10 °C/min. PT: palm trunk; PFB: palm frond base; PFM: palm frond midrib; PL: palm leaflets; PC: palm coir; FS: fruit stalk; DPS: date palm stone; FEB: fruit empty bunch; AT: *Acacia tortilis*.

The maximum peak temperature (T_{max}) ranged from 350 °C (DPS) to 467 °C (PL) and the VMC varied from 75.6% to 86.2% for PFB and *A. tortilis*, respectively (Table 4). It is known that the lower the T_{max} of the residue, the easier it is to ignite a fuel [63]. Accordingly, it can be said that all the date palm residues are easier to ignite as fuels compared to *A. tortilis*, except PL and PC. This may be attributed to the higher content of lignin of PL and PC compared to the other materials. The ignition temperature (T_i), the temperature at which a sudden fall is seen in the TGA curve, was less than 300 °C and ranged from 228 °C (PFB) to 292 °C (PC). As the VMC increases, the ignition temperature falls and char becomes more reactive [63]. It is clear from Table 4 that the increase in the weight loss increases the volatile matter obtained from the TGA curve. The maximum weight loss, which occurred in the active pyrolysis zone, was ranged from about 46% for PFB to 66% for PC while the VMC ranged from about 76% to 86% for the same residues. It was reported that thermal decomposition of hemicelluloses occurs at temperatures ranging from 150 to 350 °C, while cellulose decomposes in the range of 275 to 350 °C [61]. However, lignin gradually decomposes at temperatures between 250 and 500 °C. Extractives and inorganic materials decompose at 187.9 °C.

Table 4. Devolatilization * of the date palm residues and *A. tortilis*.

Feedstock	Ignition Temperature (°C)	Peak Temperature T_{max} (°C)	Weight Loss [1] (%)	Residue (%)
PT	235	385	51.6	20.65
PFB	228	379	46.3	24.39
PFM	252	379	51.4	22.01
PL	279	467	55.7	22.91
FS	253	379	59.1	18.18
FEB	261	378	60.9	17.76
DPS	282	350	58.6	21.51
PC	292	412	66.2	13.77
Acacia tortilis	**274**	**398**	**58.5**	**16.53**

* These data are extracted from TGA curve with heating rate 10 °C/min in nitrogen. [1] In the zone of active pyrolysis.

3.4. Fuel Characteristics of the Date Palm Residues

Statistically, the differences among the eight date palm residues in terms of heating value (HV) were highly significant. The fuel characteristics for the eight date palm cultivars as well as the wood of *A. tortilis* are presented in Table 5. In addition, a good relationship between HV and lignin content, carbon content and ignition temperature of date palm residues (Figure 2) occurred. The HVs of the residues varied from 15.5 MJ· kg^{-1} for PFB to 19.9 MJ· kg^{-1} for PC. However, the HV on the basis of ash-free dry weight (daf) had a wide range from 16.5 MJ· kg^{-1} for PFB to 22.6 MJ· kg^{-1} for PL due to the large variation in the ash content of the residues (1.3%–11.6%) as shown in Table 5. Comparing to the heating value of the wood of *A. tortilis*, it can be seen from Table 5 that except for PC and DPS, all the date palm residues gave lower values than *A. tortilis.* The energetic density of the residues, the potential energy available per unit of biomass ranged from 3.7 (PFB) to 13.3 GJ· m^{-3} (DPS). In addition, the data indicated that except for DS, all date palm residues were lower than the value obtained for the wood of *A. tortilis* (13.6 GJ· m^{-3}). The energetic density of the DPS and PC were close to the wood pellets (12 GJ· m^{-3}) and they are much higher than the remained remaining date palm residues. This result is in accordance with the finding of El May *et al.* [41] who found that the energetic density of four date palm residues ranged from 2.6 to 11.4 GJ· m^{-3}.

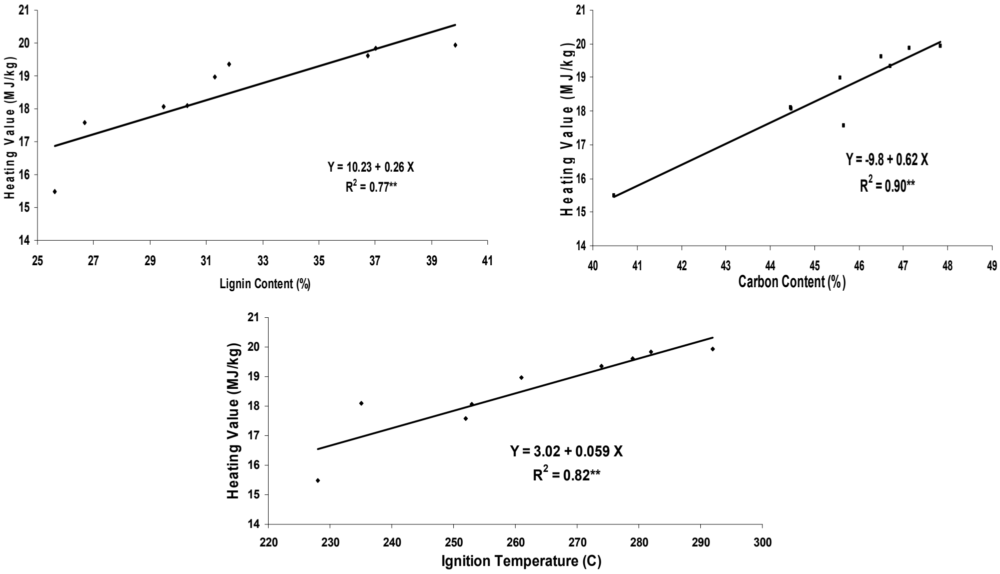


Figure 2. Relationship between heating value and lignin content, carbon content and ignition temperature of date palm residues. ** Significant at 0.01 level of probability.

Table 5. Fuel characteristics of the eight date palm residues.

Feedstock	Heating Value (MJ/kg) On Dry Wt Basis (db)	Heating Value (MJ/kg) On Ash-Free Dry Wt Basis (daf)	Energetic Density [1] (GJ/m^3)	Ash Content (%)	Fuel Value Index [2]
PT	18.10 ^{D} ± 0.3	18.80 ^{DE}	7.24	3.86 ^{c}	187
PFB	15.47 ^{F} ± 0.4	16.51 ^{F}	3.65	9.81 ^{b}	54
PFM	17.57 ^{E} ± 0.6	18.21 ^{E}	4.37	3.56 ^{c}	120
PL	19.60 ^{AB} ± 0.2	22.58 ^{A}	8.20	**15.2** ^{a}	53
FS	18.07 ^{D} ± 0.2	18.33 ^{E}	10.85	1.80 ^{e}	892
FEB	18.98 ^{C} ± 0.3	19.38 ^{D}	9.27	1.78 ^{ef}	487
DPS	19.85 ^{A} ± 0.3	20.10 ^{C}	13.25	***1.28*** ^{f}	2078
PC	19.93 ^{A} ± 0.3	20.70 ^{B}	11.88	2.90 ^{d}	309
Acacia tortilis	**19.34** ^{B} ± 0.4	**19.56** ^{CD}	**13.58**	**1.92** ^{e}	**1170**
El May *et al.* [41] [3]	15–19	-	2.6–11.4	1–15	-
Nasser [7] [4]	17–18	18–19	-	3.4–8	176–306
Nasser *et al.* [16] [5]	18–19	19–20	-	2.9–4	225–508
Nasser and Aref [28] [6]	18–21	-	-	1.8–3	1310–2350
Kataki and Konwer [29] [7]	14–22	14–22	-	0.8–4	369–2089

Each value is an average for 10 specimens ± standard deviation. Means with the same letters in column are not significantly different at 0.05 level of probability. [1] According to Alhamed [23]. [2] According to Bhatt and Todaria [47]. [3] Four date palm residues. [4] Midribs of common five date palm cultivars grown in Saudi Arabia. [5] Prunings of seven vine cultivars cultivated in Saudi Arabia. [6] Six Acacia species grown wild in Saudi Arabia. [7] Small branches of 35 tree species grown in north-east India.

The HVs of the eight date palm residues were found to be in the range of some well-known biomass fuels reported in the literature, *i.e.*, common reed (18.9 MJ/kg) [4], *Calotropis procera* (19.5 MJ/kg) [64], vine prunings (18.7 to 19.2 MJ/kg) [6], corncobs (17 MJ/kg) [1], and tobacco stems (17.8 MJ/kg) [2]. The heating values of bio-char produced from FEB ranged from 23 to 26 MJ·kg^{-1} [65]. In view of the obtained HVs and compared to other biomass fuels, the results indicated that these residues can be considered as a good source for energy production. Unfortunately, the high ash contents of all parts of the date palm, especially the PFB and PL, make them less desirable for use as a fuel source of because of the negative effect of ash on the fuel characteristics [57,66].

Generally, the results in Table 5 indicate that except for DPS, all date palm residues exhibited the lowest FVI values (53 to 892) compared with the values published in the literature for different wood species and general biomass, which might be attributed to the higher ash contents found in the date palm residues and the lower specific gravity. These results were in parallel with the findings of Nasser *et al.* [6] on vine prunings (FVI ranging from 225 to 508). On the other hand, a wide range of FVI values, from 369 for *Litsea polyantha* to 2089 for *A. nilotica*, which presented ash contents ranging from 3.6% to 0.9%, respectively, has been found [29]. This means that the ash content is the most important variable adversely affecting FVI values [6]. The FVI value of DPS is higher (2078) either than the value obtained for *A. tortilis* (1170) or than other date palm residues in the current study, which may be due to the higher bulk density and heating value as well as to low its low ash content.

The results indicated that among the eight date palm residues, the PFB and PL showed the lowest values for fuel characteristics, including HV, ash content and FVI, making it less desirable for use as fuelwood. On the other hand, DPS seems to be the most attractive of the date palm residues in this study for energy production and low cost transportation. This result is matched with the finding of El May *et al.* [41] on four date palm residues including PL, PT, PFM and DPS.

3.5. Ranking of Date Palm Residues

According to the data presented in Table 6 and using the most important measured data of the eight date palm residues in the present study, the results for a hypothetical rating are presented in Table 6. In this method, the date palm stones (DPS) showed the best value (1.9) followed by the palm coir, PC, (2.5) and *A. tortilis* (3.0), while the palm frond base (PFB) showed the poorest rating (6.3). The overall rating suggests that the DPS and PC show parameters suggesting they could be more suitable for energy production in Saudi Arabia compared to *A. tortilis* and the other date palm residues. It can be concluded that the suitability of the eight date palm residues studied here can be ranked in the following order: date palm stone > palm coir > fruit empty bunch > fruit stalk > palm leaflets > palm frond midrib > palm trunk > palm frond base. This order was established, in general, from the point of view of energy production. Unfortunately, the frond base and palm trunk are less desirable for energy production.

Table 6. Rating of the eight date palm residues regarding some measured characteristics.

Property	DPS	PC	*A. tortilis*	FEB	FS	PL	PFM	PT	PFB
Density	1	8	2	3	2	4	6	5	7
Lignin content	2	1	4	4	6	3	7	5	8
Ash content	1	5	4	2	3	9	6	7	8
Carbon content	1	1	2	3	4	2	3	4	5
Hydrogen content	1	2	3	3	4	5	4	5	6
Nitrogen content	6	1	3	2	3	5	2	4	2
Oxygen content	1	1	2	4	5	3	4	5	6
Heating value	2	1	4	5	6	3	7	6	8
Rank	1.88	2.50	3.00	3.25	4.13	4.25	4.88	5.13	6.25
Order	1	2	3	4	5	6	7	8	9

4. Conclusions

The present study investigated the suitability of different parts of date palm tree for charcoal production. It can be concluded that there are a large variations among the eight parts of the Sukkari date palm cultivar. It can be clearly seen that the date palm residues presented higher total extractives (8%–33%) and ash content (1%–15%) than either common wood species or other lignocellulosic materials. In these regard, date palm residues were found to have a medium to high content of cellulose (33%–48%) and lignin (26%–40%) and low to medium hemicelluloses content (13%–31%).

Large variations were found in proximate analysis values of the eight date palm residues. Volatile matter content ranged from 74.3% for PL to 87.5% for FEB; fixed carbon content ranged from 10.5% for PL to 17.6% for PT and the ash content ranged from 1.4% (DPS) to 15.2% (PL). It can be said that except for PL, the thermal decomposition was completed below 500 °C. The HVs of the residues varied from 15.47 $\text{MJ}\cdot\text{kg}^{-1}$ for PFB to 19.93 $\text{MJ}\cdot\text{kg}^{-1}$ for PC. However, the HV based on ash-free dry weight (daf) had a wide range from 16.5 $\text{MJ}\cdot\text{kg}^{-1}$ for PFB to 22.6 $\text{MJ}\cdot\text{kg}^{-1}$ for PL due to the large variation in the ash content of the residues (1.3%–11.6%). The FVI value of DPS was higher (2078) than the value obtained for *A. tortilis* (1170) or other date palm residues in the current study. From all the parameters studied, it would be expected that the eight parts have variations in their fuel properties and thermal behavior, where the chemical composition of these residues explain these variation. The overall ratings suggest that DPS and PC show interesting parameters, and they could be considered more suitable for energy production.

Acknowledgments: The authors would like to extend their sincerest appreciation to the Deanship of Scientific Research at King Saud University for the funding of this research through the Research Group Project # RGP-VPP-226.

Author Contributions: R.A.N. designed the experiments, wrote parts of manuscript and laboratory analyses, M.Z.M.S. wrote part of the manuscript and interpretation of the results, S.H. revised and amended the article for technical merits; H.A.A.-M., A.S.M., and M.A. analyzed some parts the data; I.M.A. contributed reagents/materials/analysis tools.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

ANOVA	Analysis of variance
CRD	Complete Randomized Design
daf	Dry ash-free fuel
db	Dry Basis
DPS	Date Palm Stones
DTG	Derivative Thermo-gravimetric
FCC	Fixed Carbon Content
FEB	Fruit Empty Bunch
FS	Fruit Stalk
FVI	Fuel Value Index
HV	Heating value
LCM	Lignocellulosic materials
LCR	Lignocellulosic Residues
MC	Moisture content
NREL	National Renewable Energy Laboratory
PC	Palm Coir
PFB	Palm Frond Base
PFM	Palm Frond Midrib
PL	Palm Leaflets
PT	Palm Trunk
TEC	Total Extractives Content
TGA	Thermo-gravimetric Analysis
T_{max}	Maximum Peak Temperature
VMC	Volatile Matter Content

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