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RESEARCH ARTICLE

Maximize utilization of date palm residues to produce environmentally friendly fuel briquettes

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ABSTRACT

This study aimed to maximize the utilization of date palm residues and convert them into an environmentally friendly form of fuel. The residues of the date palm variety Khalas (leaf fronds and whole fronds) were used to produce fuel briquettes at three moisture contents (8, 10, and 12%) and four storage times (0, 15, 30, and 45 days). The mechanical, fuel, and quality properties of these briquettes were investigated. The results showed that the leaf fronds had the best results in terms of mechanical properties and fuel quality properties of the briquettes. The best results for compressive stresses for the leaf fronds were 24.98 MPa at 10% moisture content and for the whole fronds were 4.27 MPa at 12%. The second storage period gave the best results for all briquettes at the different moisture contents. The results showed significant effects of moisture content and storage period on mechanical properties. The hydrolysis time and durability of the briquettes increased with increasing moisture content. The calorific value of leaf fronds and whole fronds briquettes ranged between (17.78 and 18.12 MJ/kg) and (16.54 and 17.78 MJ/kg), respectively. These good quality briquettes can be handled and used, especially in rural areas where other energy sources are not available.

Keywords: Calorific value; Date palm residues; Durability; Fuel value index; Modulus of elasticity

INTRODUCTION

Date palm (*Phoenix dactylifera L.*) is one of the most important commercial crops and plays an important role in the economic and social life of people in Saudi Arabia (Eissa and Alghannam, 2018, Ahmed et al., 2022a). Palm trees are considered one of the important sources of agricultural crops in Saudi Arabia. Dates are considered one of the favorite food commodities for the people of the Kingdom and enter into many food industries. The total number of palm trees in Saudi Arabia exceeded 28 million (FAOSTAT, 2023). One of the main problems of farmers is negatively affecting the surrounding environment, where they are disposed of in primitive ways such as burning or storage, leading to environmental pollution and many environmental problems that are difficult to be solved in the future.

Pruning process of the palm tree annually produces 13 leaves and 7 bunches. The calculated quantity annually extracted from this process was for fronds (120,000 tons), leaves (410,000 tons) and bunches (300,000 tons). While, the fronds and leaves residues of palm trees annually exceeded more than100,000 and 15,000 tons, respectively in Saudi Arabia (El-Juhany, 2001; Al-Sulaiman, 2003; Eissa and Alghannam, 2013 and 2018).

Agricultural residues in Saudi Arabia (especially date palm residues) are considered a secondary product within the agricultural production systems. This is a major problem for farmers and adversely affect the surrounding environment, where they are disposed of in primitive ways such as burning or storage, which leads to pollution of the environment and the many environmental problems that are difficult to be solved in the future (i.e., in next generations). It is possible to maximize their utilization by converting their into organic fertilizers, fodders, clean energy, or manufacturing them to contribute clean agriculture, protect of the environment from pollution and improve the economic and environmental conditions (Al-Sulaiman, 2003; Baliga et al., 2011; Al-Hammad, 2019, Ahmed et al., 2022b). The Briquetting technique improves

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the properties of agricultural residues in transport, storage and feeding in furnaces and combustion processes (Werther et al., 2000).

Al-Habbab, (2014) stated that from seasonal pruning in Saudi Arabia, the palm trees are produced about 15-20 fronds from each tree, which producing hundreds of thousands of tons' residues that must be invested and exploited for the benefit of this country. He also mentioned that the residues of these trees could be converted to useful products in large quantities that serve the community and contribute to the national economy such as wood, paper, fuel sources, animal feed, biomass energy, and fertilizer and building materials. With a large amount of palm residues, it is not optimized. Many farmers burn these residues for disposal, causing an increase in environmental pollution. Grover and Mishra, (1996) stated that the biomass moisture content in the extruder feeder is a most important factor. They concluded that if the residues moisture content were 8-10%, the moisture content of briquettes obtained would 6-8%. In addition, the produced briquettes were strong and free from cracks and a logical briquetting process. While the poor and weak briquettes and irregular briquetting process were produced if the moisture content is exceeded 10%.

El Saeidy, (2004) found that the main advantage of biofuel production is that it can be used without harming the environment and its advantage lies not only in contributing to the mitigation of carbon dioxide, but in also extending to other elements. The combustion test on poplar, cannabis and straw was carried out naturally in the form of branches, twigs, stems and in the form of hydraulically pressed briquettes. The combustion test results showed that the emission rates in the briquettes were uniform compared to the emission rates in the waste combustion test, which is loose material. The results showed that CO emissions from briquettes were lower than in branches. Poplar briquettes were 30% lower in CO emissions than in poplar branches, and in straw briquettes were 56%. The results were also the same for other emissions were NOx, SO_2, CO_2 and ash content.

To improve the transport, store and use processes in its original form, the solution to these problems is condensing biomass materials into pellets, briquettes. Condensation process increases the bulk density of the biomass from 40-200 kg/m^3 to 600-800 kg/m^3 (Mc Mullen et al., 2005). The burning of agricultural residues leads to air pollution, soil erosion and reduced biological activity, eventually resulting in lower yields. However, burning results in smoke and other pollutants adversely affecting air quality, visibility, and human with polluted environment as well health. (Dubey et al., 2007).

Briquettes durability is a measure of the ability of briquettes to withstand destructive forces such as pressure, impact and shear during handling and transportation. In addition, the durability values represent the relative strength of the bond between particles and particles in briquettes/granules (Nalladurai and Morey, 2010). Yassin et al. (2013) investigated the emission characteristics of the combustion of five date palm residues (date palm publications, raschis date palm, date stone and fruit stalk palm).

The current study aimed to maximize the use of date palm residues and make it an environmentally friendly fuel for use in rural areas. In addition, evaluating the effects of moisture content and storage time on the properties of the produced briquettes.

MATERIALS AND METHODS

Experimental setup

The experimental work of this study was done in Department of Agricultural Systems Engineering, College of Agricultural and Food Sciences, King Faisal University. In this study, the residues of date palm cultivars Khalas (leaf bases and whole fronds) which are produced during annual pruning of palm trees, were used. These parts were selected from the palm because they are annual residues after the harvest season and because the waste is large and occupies a large area. Initially, the studied residues were collected from a privet palm farm after the pruning's were dry. Some preliminary measurements were carried out on the samples of the residues, such as (mass, length, width and thickness). The selected residues were ground with a grinding machine in the mentioned farm. The ground materials were taken to the laboratories of the Agricultural Systems Engineering Department to determine the moisture content of the samples and prepare them for briquetting under the different treatments with the screw press.

After the pelleting process, it is generally agreed that the size of leaf fronds and total sun material should be between 6-8 mm with a powder content of 10-20% (less than 4 grids) and the moisture content should not exceed 10% (Grover and Mishra, 1996). However, due to the variety of residues that can be used for agglomeration and certain characteristics associated with each type (such as calorific value, volume, moisture content, and chemical composition), pretreatment is usually required to ensure that the residues are suitable for coal production. In this regard pretreatment processes may include drying materials to remove excess moisture and reduce volume (cutting and grinding) and preheating residues (not to exceed 300°C) to soften the fibers in the waste and loosen their structure, thereby reducing the screw press corrosion (Grover and Micra, 1996).

The effect of three different moisture contents (8, 10 and 12%) was studied according to (Grover and Mishra, 1996; El Saeidy, 2004). After determining the appropriate moisture content of the residues selected for the study, the briquetting process was carried out using the screw press machine. Briquetting is a compaction process used to increase the low bulk density of residues to high density (from 150-200 kg/m^3 to 900-1300 kg/m^3) using an auger press (see Fig 1). After completion of the briquetting process and production of the corresponding briquettes, they are stored at room temperature. After that, some measurements were performed during the storage period. The physical and mechanical properties of the briquettes were investigated during compression tests at the College of Engineering, King Faisal University. In addition, the quality properties of the produced briquettes (gas emissions, bulk density, hydrolysis time and durability) and fuel properties (calorific value, dry ash content and fuel value index) were studied.

Chopping machine

The chopping machine used in this study is shown photographically in Fig. 2. It consists of the following parts: (1). The main frame; (2) A system chopping head with a diameter of 54 cm with radial knives attached to it with bolts and rotating at 2000 rpm. (3) Feed inlet. (4) Power transmission [the power is transmitted to the cutter shaft by an electric motor with two pulleys (drive and output belts) and transmitted by four V- belts]. (5) Power source: the power of a 30 kW electric motor. (6) Output of the ground residues.

Screw press machine

The briquette screw press (type ZBJ-III) is shown in Fig. 3. It was equipped with an automatic temperature control system and has a production capacity of 230-280 kg/h. The press is driven by a 15 kW electric motor. It has 3 electric ceramic heating bands, each requiring 3 kW for operation, and has an integrated "T" stirrer with a 1.5 kW motor. The press requires a standard 380 volts, 50 Hz, 3 phase electric motor. The machine also has a control panel with an operating pressure of 100 MPa. The grinded materials are placed in a container above the machine and then compacted by the screw press under higher temperature (not higher than 300^{o}C). The rotating screw picks up the grinded materials from the feed input and compacts it, which helps to the build up a pressure gradient along the screw press. In addition, the combined effect of the internal friction in the material and the rotational speed (0.38 m/sec) of the screw causes a temperature rise in the closed system, which contributes to the heating of the material to produce the briquettes in the desired shape.

Physical properties of raw materials and briquettes

- Mean diameter, length and mass of each briquette were measured using a digital caliper and an electronic balance (EN 16127:2012).
- Moisture content: The moisture content of the samples was measured with a moisture meter (TK 100 W), range (5- 90%) with an accuracy of ± 0.5%.

Compression test

This test was carried out in the laboratories of the Department of Mechanical Engineering, College of Engineering at King Faisal University using a universal testing machine (UH-500KN, Shimadzu) Fig. 4a. Before starting the test, briquette specimens with uniform length (10 cm length and 6 cm diameter) were prepared. The specimens were placed between two metal plates on the horizontal plane of the testing machine (Fig. 4a), and the load on the specimen was constantly increased until it failed dye to fracture or cracks in the outer surface (Fig. 4b). During the measurement period, the loading stresses and strains were recorded. The main measured values from the compression test on leaf fronds briquettes were (yield stress, ultimate stress, modulus of elasticity, fracture stress and modulus of resilience) (Kaliyan and Morey, 2009).

Quality properties of briquettes

Durability

In this test, the durability of briquettes was determined according to ASABE Standard S269.4 (2003), as shown in

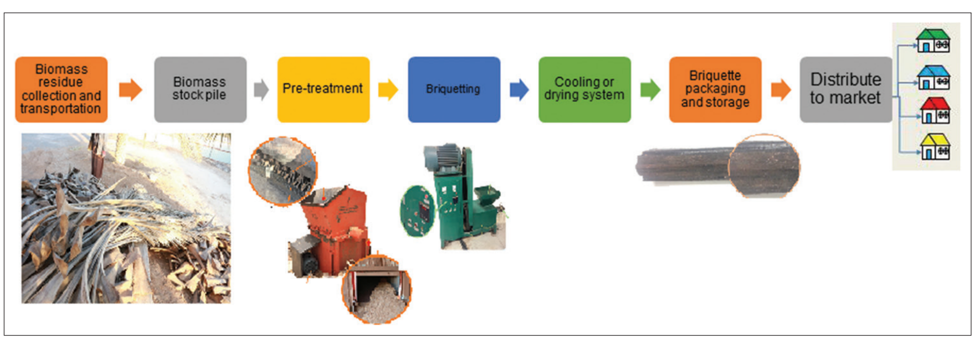

Fig 1. The flow chart of date palm residues briquetting system.

Fig. 5a. Samples of constant mass briquettes (500 g) were placed in the feed slot inside the cylinder. The manual arm was rotated at a speed of ± 50 rpm for 10 minutes, moving the samples placed in the cylinder. During the experiment, the broken particles accumulate on the bottom of the sieve.

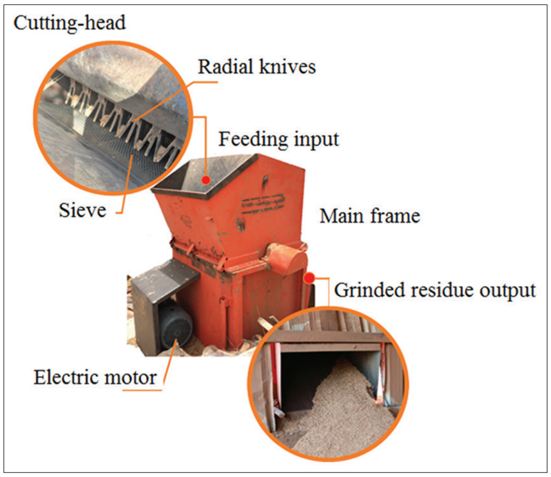

Fig 2. A photographic picture of the chopping machine.

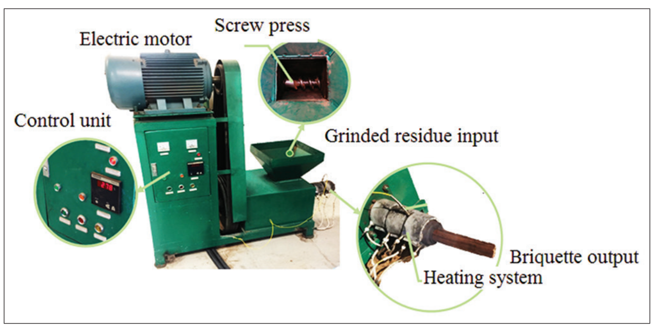

Fig 3. Briquetting press machine.

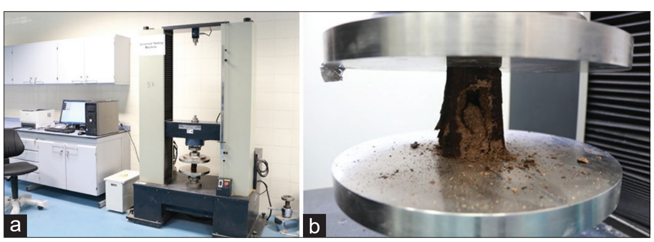

Fig 4. (a) Universal testing machine (UH-500KN, Shimadzu), (b) failed sample under compression test.

The Durability of the briquettes is expressed as the percentage ratio between the mass of briquettes remaining on the sieve at the end of the test (m_1) and the total mass of briquettes before the test (m_2), as shown in Fig. 5b. The following equation was used to calculate the durability of the briquettes (Fasina, 2008):

$$D_u = \frac{m_1}{m_2} \times 100 \quad (1)$$

Time of hydrolysis

The hydrolysis resistance of the briquettes was tested by immersing the samples in vessels filled with water and measuring the time required for complete dissolution of the sample in water (Fig. 6). (Yamnan et al., 2001) and (Debdoubi et al., 2005)

Bulk density

The bulk density of the briquettes was measured by dividing the mass of the briquettes by their volume using the following equation: (Jha et al., 2008)

$$\rho_b = \frac{M}{L \times B \times T} \quad (2)$$

Where: M, mass of sample (kg); L, B, and T is the length, width and thickness of samples, respectively.

Fuel properties and gas emissions

Gas emissions were measured using the IBRID MX6 model, as shown in Fig. 7a. Samples of constant mass (100 ± 2 g) were combusted in the combustion unit shown in Fig. 7b. The gas analyzers were placed near the outlet of the combustion unit, keeping a distance of not less than 2 cm to minimize the effect of the heat of the gases on the sensors. The emitted gases (carbon monoxide (CO), NO_2, H_2S, PID and CH_4) were measured in ppm. The measurement was performed from the beginning of the combustion process to the end of the combustion of the sample. The readings of the emitted gases were measured every five minutes and at the end, the average values of the

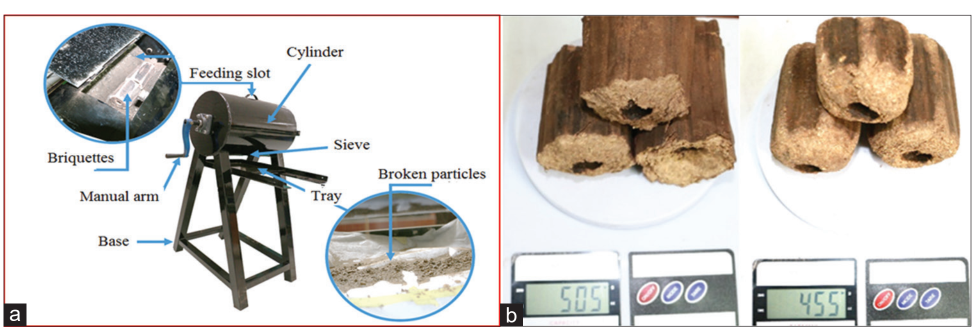

Fig 5. (a) Durability measurement unit, (b) samples before and after durability test.

sample during the combustion process were determined. The effects of different moisture contents on the fuel properties of briquettes (calorific value (CV), dry free ash (DFA) and fuel value index (FVI)) were measured. The calorific value of Khalas grade dry-based briquettes was measured according to the standard method described in (ASTM D2015-85, 1987). The fuel value index was calculated using following equation (Bhatt and Todaria, 1992):

$$\text{Fuel value index} = \frac{\text{Calorific value} \times \text{density}}{\text{Ash content}} \tag{3}$$

Where the dry ash free of briquettes was calculated according to (Nasser, 2014):

$$\text{Dry ash free} = \text{Calorific value} \times \left[1 + \frac{\text{Ash content}}{100}\right] \tag{4}$$

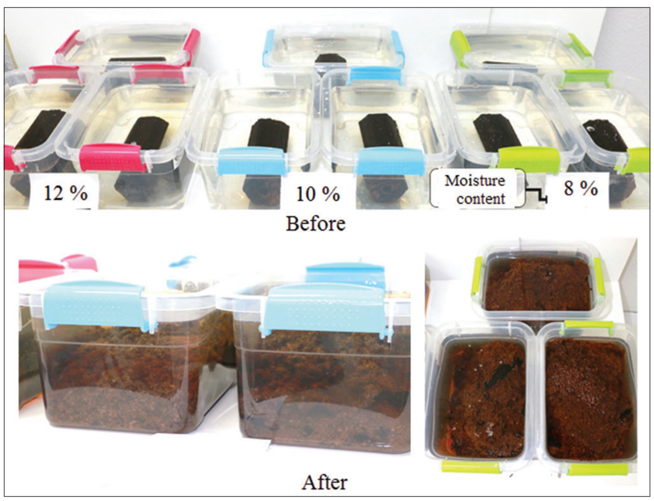

Fig 6. The resistance of the briquettes hydrolysis test.

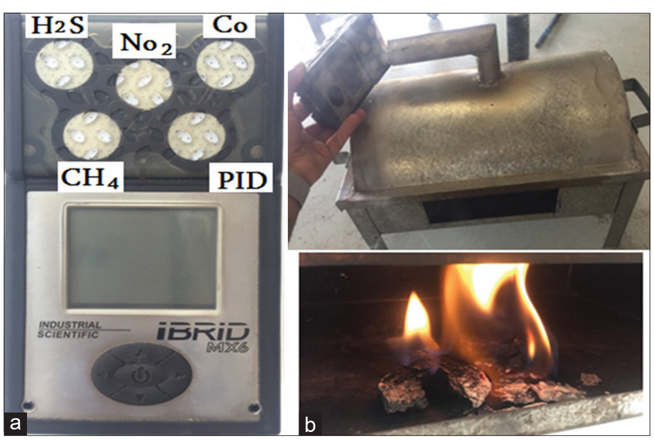

Fig 7. (a) Gases emissions analyzer (IBRID MX6 model), (b) a combustion unit.

Statistical analysis

Analysis of variance between the three levels of moisture content and four storage periods of all properties was performed using the SPSS program (SPSS. 22). The least significant difference test at the 0.05 probability level (LSD 0.05) was used to detect differences between the means of all measured properties.

RESULTS AND DISCUSSION

Effect of moisture content on compression stresses and strains of briquettes

Fig. 8 shows the effect of different moisture contents of leaf base and full frond briquettes on the values of compression stresses and strains. The results show that leaf base briquettes with moisture content of 10% had the highest compression stresses of 24.98 MPa, followed by 8% (Mc) with 19.36 MPa, while leaf base briquettes with 12% (Mc) had the lowest compression stresses of 18.89 MPa. The full frond briquettes with 12% (Mc) showed the highest value of 4.27 MPa, while the briquettes with 8% moisture content showed the lowest value of 1.82 MPa. As for the strain values of the leaf base and full frond briquettes at different moisture contents, the results showed that the leaf base briquettes at 10% (Mc) exhibited the highest value of 0.084, while at 12% (Mc) the lowest value of 0.081 was recorded. The full frond briquettes showed the highest

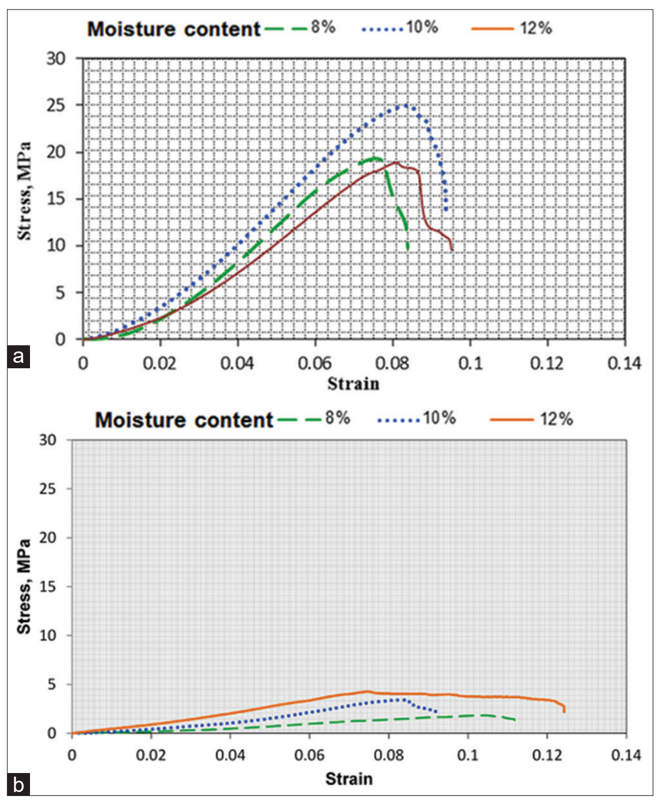

Fig 8. Effect of moisture contents on compression stresses and strains of (a) leaf bases; (b) full frond briquettes.

value of 0.105 at 8% moisture content and the lowest value of 0.075 at 12%. This is due to the fact that the samples that showed higher compression stress values have a lower deformation rate and vice versa. This behavior is reflected in the results of compression strain at all moisture contents, where the moisture content compression stress 10% had the highest value of compression stress and, in contrast, the lowest value of the compression strain.

The achieved results are also consistent with Grover and Mishra (1996), where moisture content in raw materials is between 8-10%, briquettes will be strong, not crack. However, when the moisture content more than 10%, produces poor and weak briquettes and irregular briquetting process.

Effect of moisture content on compression stresses and strains of briquettes

The data in Fig. 9 show the effect of storage time and different moisture contents on compression stress and strain values of the leaf base and full frond briquettes. The highest values of the leaf base and full frond briquettes at 8% moisture content were 19.36 MPa, 0.076 and 4.68 MPa, 0.072, respectively during the first and second storage periods and then decreased until the end of the storage process. The lowest values were measured during the last storage period with 14.21 MPa, 0.073 and 1.26 MPa, 0.205 for the leaf base and full frond briquettes, respectively.

While the highest values of compression stresses and strains at 10% moisture content were recorded for the leaf bases and full frond briquettes during the first and second storage periods 24.98 MPa, 0.084 and 6.93 MPa, 0.089, respectively, they then began to decrease. The lowest values were recorded at the end of the storage period (13.64 MPa, 0.087 and 4.11 MPa, 0.082) for leaf base and full frond briquettes, respectively. On the other hand, at a moisture content of 12%, the highest values of compression stresses and strains were recorded for the leaf bases and full frond briquettes during the first and second storage periods (18.90 MPa, 0.848 and 9.26 MPa, 0.071), respectively.

The lowest values were recorded at the end of the storage period (9.78 MPa, 0,076 and 4.35 MPa, 0.129) for the leaf bases and full frond briquettes, respectively, which is lower than the moisture content of 8 and 10%. These results are

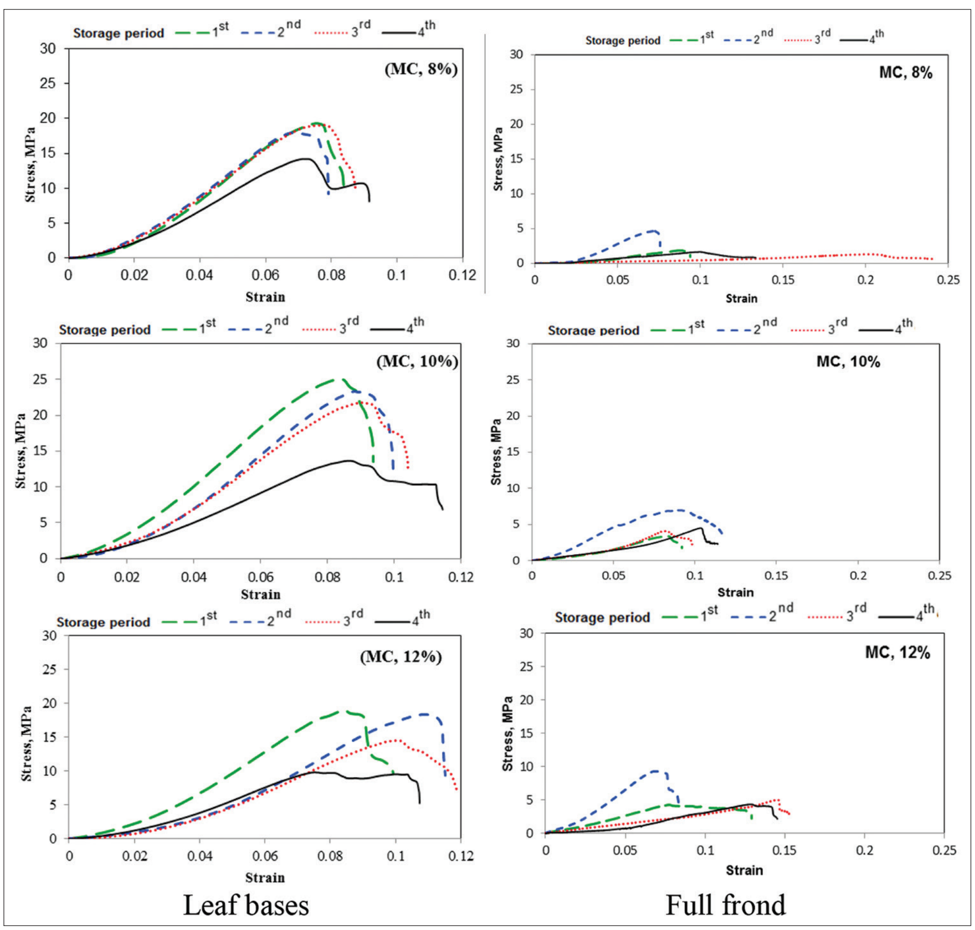

Fig 9. Effect of storage periods (day) under moisture contents (8, 10, and 12%) on compression stresses and strains of leaf bases and full frond briquettes.

in agreement with those of (Eissa and Alghannam, 2018) who reported that "the maximum compression stress was found in the lower part of the palm fronds. This could be due to the fact that they have more fibers and thicker stem wall than the upper part". This could also be due to the lower resistance and elasticity values of the briquettes with increasing storage time, as well as the change in moisture content of the briquettes during long storage periods. It is also clear that the compression stress values of the briquettes at different moisture contents decreased with increasing storage time for the same reason as mentioned previously. The results also showed that the moisture content (10%) gave the best results and the second storage time gave the best results at different moisture contents.

Effect of moister contents and storage time on mechanical properties of briquettes

The data in Table 1 show the significant effects of three moisture contents (8, 10 and 12%), and four storage periods (zero storage, 15, 30 and 45 days) on the mechanical properties of leaf basis and full frond briquettes (yield stress, ultimate stress, modulus of elasticity, fracture stress and modulus of resilience). The results showed that the effects of moisture content and the storage periods on all mechanical properties were highly significant for all briquettes.

Tables 2 and 3 below show the least significant difference (LSD) analysis of the effects of moisture content and storage period on the mechanical properties of the leaf base and full frond briquettes. The data showed that there was a higher significant effect between the different values of mechanical properties.

The interactions between the three moisture contents on the mechanical properties of the briquettes are shown in Table 2. The results of leaf base briquettes showed a significant effect between the moisture content (10%) compared to the other moisture contents (8, 12%) for all mechanical properties of the briquettes except the modulus of elasticity and resilience, while the results showed a higher significant effect between the values at moisture content (8%) and (12%) only for the modulus of elasticity and resilience only. However, full frond briquettes showed the greater significant differences between all moisture contents for all mechanical properties, except that the interaction between moisture contents (8, 10%) was nonsignificant for the modulus of resilience Table 2.

On the other hand, the interactions between the different storage periods on the mechanical properties of the briquettes were listed in Table 3. The results of the leaf

Table 1: Analysis variance of moisture contents and storage periods on mechanical properties of leaf basis and full frond briquettes

		dF	Yield stress (Mpa)	Ultimate stress (Mpa)	Modulus of elasticity (Mpa)	Fracture stress (Mpa)	Modulus of resilience (Mpa)
Moisture contents	Leaf bases	2	0.021*	0.047*	0.002**	0.044*	0.000**
	Full frond	2	0.000**	0.000**	0.000**	0.000**	0.000**
Storage periods	Leaf bases	3	0.000**	0.000**	0.000**	0.002**	0.000**
	Full frond	3	0.000**	0.000**	0.000**	0.000**	0.000**
Moisture contents X Storage periods	Leaf bases	6	0.715^{NS}	0.708^{NS}	0.574^{NS}	0.662^{NS}	0.518^{NS}
	Full frond	6	0.002**	0.001**	0.000**	0.001**	0.015*
Mean/Standard Errors	Leaf bases	-	15.88/0.40	17.96/0.45	295.17/5.69	9.56/0.307	823.06/18.72
	Full frond	-	3.75/0.12	4.53/0.14	66.66/2.60	2.32/0.07	226.8/9.43

*Significant at $P<0.05$ **High significant at $P>0.01$ ^{NS}Nonsignificant on 1% and 5%.

Table 2: Analysis the effect of different moisture contents at the least significant difference (LSD) on mechanical properties of leaf basis and full frond briquettes

			Yield stress (Mpa)	Ultimate stress (Mpa)	Modulus of elasticity (Mpa)	Fracture stress (Mpa)	Modulus of resilience (Mpa)
Leaf bases	8%	10%	0.01**	0.025*	0.207^{NS}	0.034*	0.000**
		12%	0.654^{NS}	0.836^{NS}	0.001**	0.909^{NS}	0.000**
	10%	8%	0.01**	0.025*	0.207^{NS}	0.034*	0.000**
		12%	0.027*	0.04*	0.014*	0.026*	0.055^{NS}
	12%	8%	0.654^{NS}	0.836^{NS}	0.001**	0.909^{NS}	0.000**
		10%	0.027*	0.04*	0.014*	0.026*	0.055^{NS}
Full frond	8%	10%	0.000**	0.000**	0.001**	0.000**	0.075^{NS}
		12%	0.000**	0.000**	0.000**	0.000**	0.000**
	10%	8%	0.000**	0.000**	0.001**	0.000**	0.075^{NS}
		12%	0.000**	0.000**	0.001**	0.000**	0.000**
	12%	8%	0.000**	0.000**	0.000**	0.000**	0.000**
		10%	0.000**	0.000**	0.001**	0.000**	0.000**

*Significant at $P<0.05$ **High significant at $P>0.01$ ^{NS}Nonsignificant on 1% and 5%.

Table 3: Analysis the effect of different storage periods at the least significant difference (LSD) on mechanical properties of leaf basis and full frond briquettes

			Yield stress (Mpa)	Ultimate stress (Mpa)	Modulus of elasticity (Mpa)	Fracture stress (Mpa)	Modulus of resilience (Mpa)
Leaf bases	1st	2nd	0.535^{NS}	0.672^{NS}	0.223^{NS}	0.800^{NS}	0.243^{NS}
		3rd	0.233^{NS}	0.162^{NS}	0.019*	0.341^{NS}	0.590^{NS}
		4th	0.000**	0.000**	0.000**	0.001**	0.002**
	2nd	1st	0.535^{NS}	0.672^{NS}	0.223^{NS}	0.800^{NS}	0.243^{NS}
		3rd	0.076^{NS}	0.074^{NS}	0.001**	0.232^{NS}	0.521^{NS}
		4th	0.000**	0.000**	0.000**	0.000**	0.000**
	3rd	1st	0.233^{NS}	0.162^{NS}	0.019**	0.341^{NS}	0.590^{NS}
		2nd	0.076^{NS}	0.074^{NS}	0.001**	0.232^{NS}	0.521^{NS}
		4th	0.002**	0.003**	0.002**	0.009**	0.001**
	4th	1st	0.000**	0.000**	0.000**	0.001**	0.002**
		2nd	0.000**	0.000**	0.000**	0.000**	0.000**
		3rd	0.002**	0.003**	0.002**	0.009**	0.001**
Full frond	1st	2nd	0.000**	0.000**	0.000**	0.000**	0.000**
		3rd	0.515^{NS}	0.998^{NS}	0.021*	0.947^{NS}	0.208^{NS}
		4th	0.527^{NS}	0.759^{NS}	0.163^{NS}	0.558^{NS}	0.008**
	2nd	1st	0.000**	0.000**	0.000**	0.000**	0.000**
		3rd	0.000**	0.000**	0.000**	0.000**	0.000**
		4th	0.000**	0.000**	0.000**	0.000**	0.003**
	3rd	1st	0.515^{NS}	0.998^{NS}	0.021*	0.947^{NS}	0.208^{NS}
		2nd	0.000**	0.000**	0.000**	0.000**	0.000**
		4th	0.985^{NS}	0.761^{NS}	0.309^{NS}	0.514^{NS}	0.125^{NS}
	4th	1st	0.527^{NS}	0.759^{NS}	0.163^{NS}	0.558^{NS}	0.008**
		2nd	0.000**	0.000**	0.000**	0.000**	0.003**
		3rd	0.985^{NS}	0.761^{NS}	0.309^{NS}	0.514^{NS}	0.125^{NS}

*Significant at $P<0.05$ **High significant at $P>0.01$ ^{NS}Nonsignificant on 1% and 5%.

base briquettes showed higher significant effects between the fourth storage period (45 days) and the other storage periods (0, 15 and 30 days), while the interaction between the first, second and third storage periods showed nonsignificant effects for all mechanical properties of the briquettes. Also, the results of the full frond briquettes showed a higher significant difference between the second storage period and the other storage periods and a nonsignificant difference between the first, third and fourth storage periods for all mechanical properties of the briquettes Table 3.

The effect of moisture content and storage period on the mechanical properties of the leaf base briquettes were outlined in Fig. 10. The results for the effect of different moisture contents on the mechanical properties showed the lowest values for all mechanical properties between 8 and 12% moisture content. At 10% moisture content, the highest values were obtained for all mechanical properties except the modulus of elasticity. Also, the results for the effect of different storage periods on the mechanical properties of leaf base briquettes showed that the second storage period had the highest values for all properties, except for the fracture stress.

This indicates the importance of briquetting the leaf bases residues at 10 % moisture content, and briquettes handling during the second period of storage compared to other storage periods.

On the other hand, the effect of moisture contents and storage periods on mechanical properties of full frond briquettes were sketched in Fig. 11. Results recorded the lowest values at 8% moisture content for all mechanical properties, while the moisture content 12% recorded the highest values for all mechanical properties.

As well as, results showed that the second storage period recorded the highest values for all properties than other storage periods. In addition, this indicates the importance of briquetting the full frond residues at 12% moisture content, and briquettes handling during the second period of storage compared to other storage periods.

Generally, from the achieved results of mechanical properties of date palm residues and how are affected by moisture contents and storage periods noted that the values of all mechanical properties of leaf bases residues were higher than that of full frond. This may be due to (Eissa and Alghannam, 2018**)**, where thay attributed the increase in values bending and fracture forces of fronds resdiues at the bottom regions than other to the accumulation of lignin, which increases the hardness by decrease moisture content.

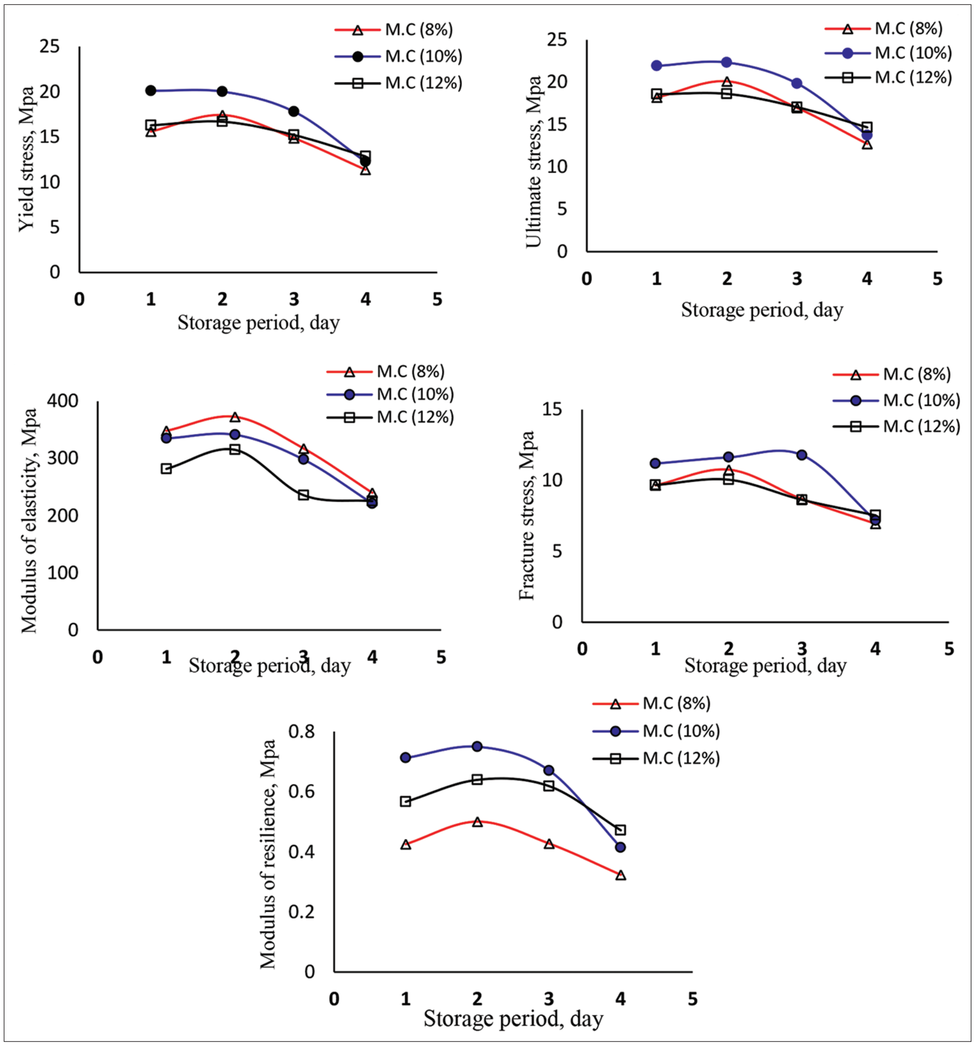

Fig 10. Effect of different storage periods and different moisture contents on mechanical properties of leaf basis briquettes.

Quality properties of briquettes

Table 4 shows the analysis of the effects of three of moisture contents (8, 10 and 12%) and two types of palm residues (leaf bases and full frond) on the quality properties of briquettes (hydrolysis time, durability and bulk density). The results showed higher significant effects between the type of residues and the durability and bulk density properties, while the residues had nonsignificant effect on the time of hydrolysis and vice versa on the moisture content and quality properties of briquettes.

Time of hydrolysis

The results presented in Table 5 show the analysis of the effects of different moisture contents on the quality properties of the briquettes (hydrolysis time, durability and bulk density). It was found that increasing the moisture content from 8 to 12% increased the hydrolysis time of the briquettes from 70 to 540 minutes and from 93 to 534 minutes for leaf base and full frond, respectively. These results are in agreement with those of (Eissa and Alghannam, 2018). And moisture content (12%) recorded the highest time for hydrolysis.

Durability

The results in Table 5 show the effects of different moisture contents on the durability of the briquettes. The results also show that increasing the moisture content from 8 to 12% increases the durability of briquettes from 97.4 to 99.2% and from 82 to 87.5% for leaf base and full frond briquettes, respectively. The lower moisture content of the briquettes the more likely they are to disintegrate due to frictional forces during transportation and handling. In general, the higher durability values can be rattributed to the high percentage of lignin in the leaf briquettes compared to the full frond briquettes. These results do not agree with those of (Eissa and Alghannam, 2018) who reported that as moisture content increases, the durability decreased.

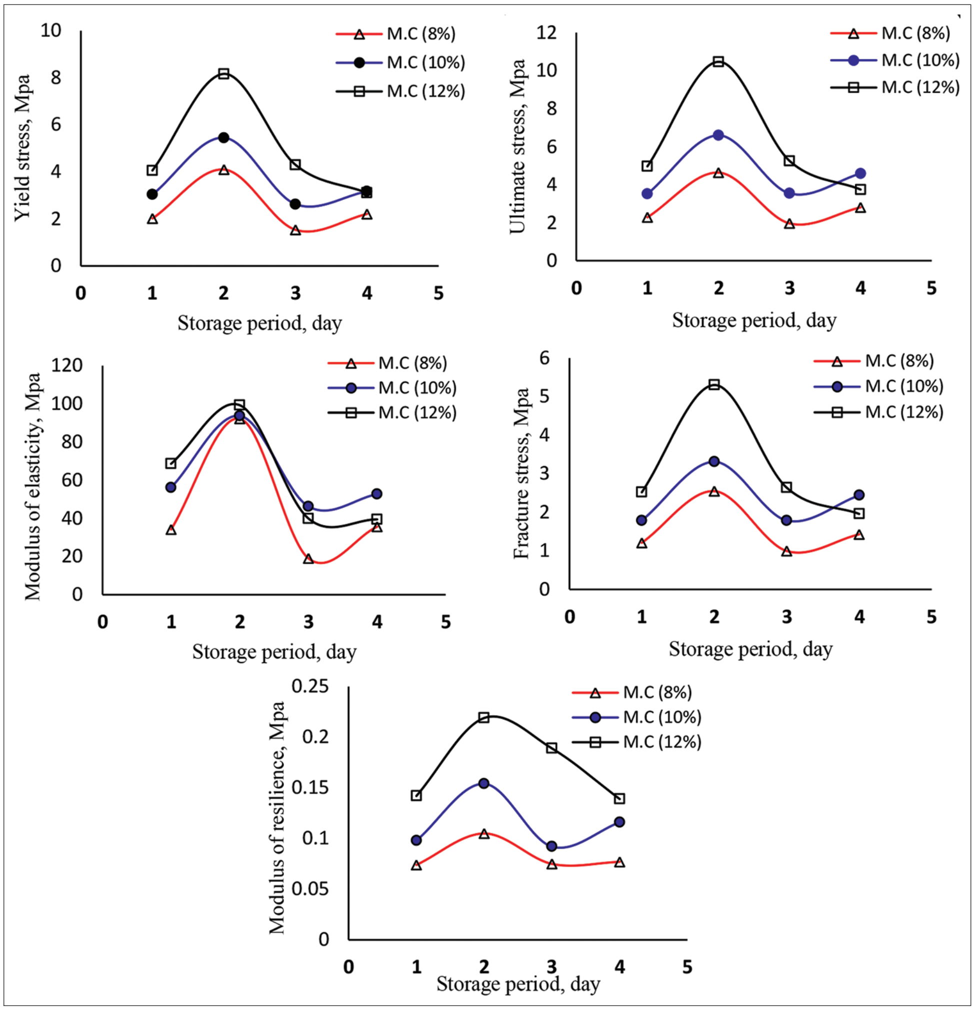

Fig 11. Effect of different storage periods and different moisture contents on mechanical properties of full frond briquettes.

Table 4: Analysis variance of moisture contents and type of palm residues on quality properties of briquettes

	dF	Time of hydrolysis (min)	Durability (%)	Bulk density (kg/m³)
Type of residues	1	0.204^{NS}	0.000**	0.006**
Moisture contents	2	0.000**	0.522^{NS}	0.253^{NS}
Type of residues X Moisture contents	6	0.000**	0.782^{NS}	0.274^{NS}

*Significant at P<0.05 **High significant at P>0.01 ^{NS}Nonsignificant on 1% and 5%.

Table 5: Effect of different moisture contents on quality properties of briquettes

	Moisture contents (%)	Time of hydrolysis (min)	Durability (%)	Bulk density (kg/m³)
Leaf bases	8	70	97.4	940-1230
	10	460	98.7	1195-1205
	12	540	99.2	1245-1250
Full frond	8	93	82	1055-1110
	10	96	85	1075-1105
	12	534	87.5	1075-1115

Bulk density

Bulk density of briquettes is one of the most important quality properties. The uniformity and density of the briquettes after the briquetting process is a measure of the pressure of the residue that contributes to the storage space occupied by the briquettes compared to the size of the waste before cutting and briquetting.

The results listed in Table 5 show that the bulk density values at different moisture contents of 8, 10 and 12% ranged between (940-1230, 1195-1205 and 1245-1250 kg/m^3) and (1055-1110, 1075-1105 and 1075-1115 kg/m^3) for leaf base and full frond briquettes, respectively. However, no significant effects were found between the values of the three moisture contents 8, 10 and 12% and the bulk density of the briquettes.

Fuel properties and gases emission

The effects of moisture content on the fuel properties of the briquettes after the combustion process were shown in Table 6. The data showed that the average of calorific

Table 6: Effect of different moisture contents on fuel properties and gas emissions of briquettes

	Moisture contents (%)	Time of combustion (min)	Heating value (MJ/kg)		Fuel value index	Gas Emissions				
			Heating value	Dry free Ash		No_2 Ppm	H_2S ppm	CO ppm	PID Ppm	CH_4 ppm
Leaf bases	8	34	18.12	18.84	489.06	1.73	2.80	416.57	61.01	0.26
	10	28	18.00	18.61	635.29	2.63	4.14	579.86	60.87	0.14
	12	25	17.78	18.38	658.18	2.64	4.54	617.57	46.11	0.10
Full frond	8	37	17.89	18.59	481.74	0	5.86	438.29	62.91	0.20
	10	30	17.67	18.27	566.48	0.49	6.40	748.14	61.09	0.16
	12	26	16.54	17.12	537.43	1.40	8.91	927	59.51	0.10

value of the leaf base briquettes ranged from 17.78 MJ/kg (12%) to 18.12 MJ/kg (8%), while the calorific value of the full frond briquettes was lower than that of the leaf base briquettes, where it ranged from 16.54 MJ/kg (12%) to 17.78 MJ/kg (8%). Similar results for heating value were recorded for different residues (Nasser et al., 2014; Komulainen et al., 2008; Hindi, 2013 and Pesevski et al., 2010). The dry ash content data revealed that the values for leaf bases briquettes ranged from 18.38 MJ/kg (12%) to 18.84 MJ/kg (8%), and for full frond briquettes the values ranged between 17.12 MJ/kg (12%) to 18.59 MJ/kg (8%). Also, the values in leaf bases residues were higher than full frond. Results for heating value and ash content indicated that the leaf bases and full frond briquettes can be used to produce the thermal energy. However, as a result of the high ash contents of date palm residues especially (leaf bases and full frond) makes it somewhat undesirable for use as a source of fuel, as it adversely effects on the full properties (Goel and Behl, 1996; Nasser et al., 2014). Results for fuel value index also was listed in Table 6. Values for leaf bases ranged between 489.06 (8%) to 658.18 (12%), also ranged between 481.74 (8%) to 566.48 (10%) for full frond briquettes. The values of fuel value index gained in this study is similar that results were reported by (Nasser et al., 2014; Kataki and Konwer, 2002). The variances in fuel value index may indicate adversely effect of the ash content on the fuel value index value.

The gases emission from combustion of briquettes is an important factor to evaluate the quality properties of date palm briquettes. The effect of moisture contents on the percentage of gases emitted from combustion, i.e. (NO_2, H_2S, CO, PID and CH_4) were listed in Table 6. The results showed that the average gases emission values of NO_2, H_2S, CO, PID and CH_4 at moisture contents 8, 10 and 12% were ranged between (1.73-2.64 ppm, 2.8-4.14 ppm, 416.57-617.57 ppm, 46.11-61.01 ppm and 0.1-0.26 ppm) and (0-1.40 ppm, 5.86-8.91 ppm, 438.29-927 ppm, 59.51-62.91 ppm and 0.10-0.20 ppm) for leaf bases and full frond briquettes, respectively. Also from results, it is clear that the emission gases percent from combustion of briquettes were higher in full frond residues than leaf bases except the No_2 gases were higher in leaf bases than full frond. This may be referring to contain the date palm fronds the leaves and forks, which may increase the fumes when combusted and thus the proportion of gases emitted. It was also observed that the combustion time decreases with increasing moisture contents from 8 to 12% for two type of residues Table 6.

The gas emissions increase with moisture content from 8% to 12% except for NO_2 and CH_4. This result agreed with (Eissa and Alghannam, 2018; Gamea et al., 2012), they reported that the gases emission of combustion was increasing by increased the moisture content of residues. The results also matched with (Obernberger et al., 2006) in which they found by increasing biomass moisture content affects its behavior during pyrolysis in the combustion process, resulting changing in the physical properties and on the type of the pyrolysis gases.

CONCLUSIONS

No doubt that the briquetting process of the date palm residues into briquettes could reduce costs and problems with handling, transportation, storage, and utilization of low bulk density materials. As well as, reduce the undesirable environmental effects resulting from the accumulation of these residues and their disposal by burning. Type of residues, moisture contents and storage periods play important roles in evaluating the quality of the resulting briquettes and their effects were studied. The moisture content (10%) was recorded the best quality properties for leaf bases briquettes through different storage periods than full frond residues where the 12% moisture content recorded the best properties. Also, the second storage period (15 days) recorded the best values of quality properties through different moisture contents. The higher mechanical properties values were recorded at leaf bases than full frond briquettes through the second storage period. Also the higher values of quality properties (time of hydrolysis, durability and bulk density) were 540 mins, 99.2% and 1245-1250 kg/m^3 for leaf bases briquettes, respectively at the moisture content (12%). The heating value of leaf bases and full frond briquettes ranged from (17.78 to 18.12MJ/kg) and (16.54 to 17.78MJ/kg). Results of gases emission (NO_2, H_2S and CO) during combustion process were increased by increasing the moisture content from 8% to 12%, while the values of gases (PID, CH_4) were decreased by increasing the moisture content of briquettes.

CONFLICT OF INTEREST

The authors do not declare any conflict of interest.

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Authors contribution

Hassan Al-Hashem, Mostafa Azam conceived and designed the experiments; Mostafa Azam and Abdulrahman Al-Hammad carried out– experiments; Mostafa Azam and Abdulrahman Al-Hammad analyzed the data; Hassan Al-Hashem, Mostafa Azam wrote the article.

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