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Article

Effect of Date Palm Cultivar, Particle Size, Panel Density and Hot Water Extraction on Particleboards Manufactured from Date Palm Fronds

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Abstract: The objective of this work was to evaluate some of the important physical and mechanical properties of particleboard panels manufactured from three different cultivars of date palm (*Phoenix dactylifera*) fronds, namely Saqui, Barhi and Sukkari. Experimental panels were manufactured from hot water extracted and non-extracted, and fine and coarse particles of the raw material under two target panel densities of 650 and 750 kg/m^3. Bending properties and internal bond strength, along with dimensional stability in the form of thickness swelling, water absorption, and linear expansion of the samples was tested. Based on the findings of this work, panels manufactured from high density level and Saqie cultivar, as well as fine particles, had better performance for their mechanical properties. The effect of hot water-treatment had less robust mechanical and physical properties. It appears that date palm fronds are underutilized resources that have the potential to be used in the manufacture of value-added panel products.

Keywords: date palm fronds; particleboard; particle size; strength properties; hot water treatment; dimensional stability

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1. Introduction

Date palm (*Phoenix dactylifera*) is a significant agricultural crop thought to have originated from the lands around the Arabian Gulf in Saudi Arabia [1]. The arid climate of Middle Eastern countries is ideal for date plantations and Saudi Arabia is one of these countries, possessing a major share of date production with seven million tons in the region [2]. There are more than 120 million date palm trees in different countries worldwide. Over two-thirds of such palms are in Arab countries and it is estimated that there are 62 million trees in the Middle East and North Africa [3].

In general, the date palm tree has an average production life of 150 years and the trees are pruned annually to eliminate broken leaves to enhance the quality of the dates. Once the date palms' fruit are harvested, large quantities of date palm rachis and leaf waste accumulates every year in agricultural lands of different countries. It is estimated that 100,000 tons/year of date palm fronds and 15,000 tons of leaves are created as a result of the pruning process in Saudi Arabia [4], and these estimations might be doubled in recent years. Both pruning and cutting old trees produces a substantial amount of biomass that is currently not efficiently and effectively used in Saudi Arabia. Burning and land filling are some of the current practices, creating significant environmental problems. Bashah [5] reported that the raw material from palm waste and residues is likely to be highly flammable if left on the ground for a long time. Thus, innovative ways of using this abundant renewable resource should be found [6]. One of these ideas is to use such natural fibers in natural fiber composites suitable for different industrial applications to meet the increasing demand in renewable and biodegradable materials [7].

The limited availability of wood resources due to the depletion of natural and plantation forestland has increased the cost of the raw material. As a result of limited raw material, supply waste from lumber manufacture using non-wood based agricultural products is becoming a substitute raw material supply in particleboard production. However, having very few domestic wood resources in Saudi Arabia and the surrounding countries, utilization of non-wood lignocellulosic fiber resources such as date palm could become ideal as a raw material for the manufacture of value-added panel products.

Date palm fronds, having rich fiber content, were investigated to be used as raw material for experimental particleboard manufacture in several past works [8–11]. The four investigations above revealed that particleboard panels made from date palm fronds resulted in satisfactory mechanical and physical characteristics. Basic physical and mechanical properties of experimental particleboard panels from date palm fronds have also been evaluated and studied [10]. Although there are many cultivars of date palm, three of them, namely Barhi, Saqie, and Sukkari, are the most common cultivars in Saudi Arabia. However, there is no or very little information on the properties of particleboard panels manufactured from these three different cultivars of date fronds regarding the function of their particle size and treatment with water.

Therefore, the objective of this work was to determine both physical and mechanical properties of particleboard samples made from fine and coarse frond particles of the Barhi, Saqie, and Sukkari cultivars of date palms and the effect of using hot water extraction on the panel properties. It is expected that the initial data from this work will aid in the consideration of using such underutilized species to manufacture value-added panel products so that a major environmental problem can possibly be solved to a certain extent in Saudi Arabia.

2. Methods

2.1. Frond Materials

Fronds of three date palm cultivars, namely: Barhi, Saqie, and Sukkari were collected from date palm farms in Al-Kharj located 100 km east of Riyadh, Saudi Arabia. First, leaflets were mechanically stripped from the frond stalks using a commercially manufactured stripper machine. Later, these stalks were cut into sections with 150 mm length before they were converted into particles in a laboratory ring flaker machine (Model BX-466, from Changzhou Jinmu Forestry Machinary Co. Ltd, Changzhou, China). Figure 1 illustrates date palm fronds after the leaflets were stripped and the ring flaker machine used for flaking the fronds.

Figure 1. Date palm fronds without leaflets and the ring flaker machine (BX-466).

A shaker-type screen (domestically manufactured) was employed to classify the obtained raw material into different flake and particle size classes through the following square screen openings: class A (<2.54 mm); class B (2.54 mm < B < 1.27 mm); class C (1.27 mm < C < 0.64 mm); class D (0.64 mm < D < 0.25 mm); class E (0.25 mm < E < 0.12 mm); and class F (≥ 0.12 mm). The average percentage of the obtained particle size was 1.7, 11.9, 26.8, 32.4, 24.4 and 1.8% for abovementioned size class, respectively. In our experiment, only the two class categories of D and E were used as they considered particleboard particles, which would be mentioned later in the text as coarse particles (class D) and fine particles (class E). Classes A, B, and C were considered as flakes and were used in another study for manufacturing oriented strand board [11].

To study the effect of hot water extraction on the panel's performance, half of the obtained particles (both sizes) were soaked in a hot water container at a fixed temperature of 80 ℃ for 16 h to eliminate the extractive and sugar contents from the raw material. In the next step, particles exposed to the hot water treatment were extracted with distilled water at room temperature and dried in a laboratory oven dryer to 3% moisture content along with un-extracted particles used in controlled panels. The particles were stored inside plastic bags in an ordinary room to maintain constant 3 percent moisture content at 22 percent relative humidity and 21 ℃ ± 1 ℃ until they were used.

2.2. Fiber Length Determination

Thin chips obtained from the fronds samples assigned for fiber-length determination were macerated in a 1:1 (by volume) solution of glacial acetic acid and 30 percent hydrogen peroxide at 60 °C for 48 h. After delignification was completed, the macerated fibers were washed several times, with mild shaking in distilled water, and then stained with Safranin. Lengths of 50 randomly selected fibers from each sampling specimen were measured in a wet condition to the nearest 0.01 mm, using a projection microscope connected to a TV screen.

2.3. Specific Gravity Determination

Specific gravity of fronds' lignocellulosic materials was determined according to American Standard Testing Methods [12]. This standard is used to evaluate the engineering performance of wood-based panels, such as particleboard, medium density fiberboard, and hardboard. It was based on oven-dry weight and green volume measured using displacement method.

2.4. Chemical Determinations of Date Palm Cultivars

2.4.1. Extractives Content Determination

The extractives content of each material was determined according to the American Standard Testing Methods [13] in three steps of 4 h each, using a Soxhlet apparatus. The percentage of extractives was calculated based on the oven-dry weight of sawdust samples.

2.4.2. Cellulose Content Determination

Cellulose was determined by the treatment of extractive-free sawdust meal with nitric acid and sodium hydroxide: one gram of extractive-free sawdust meal was treated with 20 mL of a solution of nitric acid 3% in a flask and was boiled for 30min. The solution was filtered in crucible G3. The residue was treated with 25 mL of a solution of sodium hydroxide 3% and was boiled for 30 min. The residue was filtered, washed with warm water to neutral filtrate, oven dried, and weighed [14].

2.4.3. Hemicelluloses Content Determination

Hemicellulose content was determined by the treatment of extractive free wood meal (1–2 g) with 50–100 mL sulfuric acid 2% and boiled for 1 hr. under a reflex condenser and filtrated in crucible G2. After that the residue was washed with 500 mL of hot distilled water to free the acid, and the contents were dried in an oven at 105 ± 2 °C, cooled in a desecrator, and weighed [15].

2.5. Anatomical Study of the Frond Midrib Segments

Anatomical study of midrib segments in respect of vascular bundles (VB) density, vessel dimension, vessel wall thickness, type of end wall, and vessel density per vascular bundle was performed on transverse (TS), tangential (TLS) sections. Data on VB density, vessel dimension, vessel wall thickness, vessel density/VB were collected from the sections of abaxial and adaxial surface area covering from the periphery up to the center of the basal and middle segments of the midrib. All the vessels present in the VB from the periphery up to the center of the midrib segments were measured on an Olympus CX41 (Olympus Corporation, Shinjuku-ku, Tokyo, Japan), Japan microscope, in respect of radial diameter, tangential diameter, and vessel wall thickness. Analysis of area fraction of vascular bundles, vessels lumen, fiber transverse wall, and ground parenchymatous tissue in the basal and middle segments of each replicate (frond) in each cultivar was done on an Olympus BX 51 microscope (Olympus Corporation, Shinjuku-ku, Tokyo, Japan).

2.6. Panel Manufacturing

Particles were oven dried at 90 ± 5 °C for 40–48 h until the moisture content (MC) of particles reached and equilibrated to 3% MC (by taking MC samples, until having two constant weights). Particles were then blended with urea-formaldehyde resin (UF, TIONES 5100C, from BOSSN Chemicals Co., Beijing, China) using a pneumatic spray gun and mixing the shaker for 10 minutes at room temperature. Based on the oven dry particle weight, a 10% UF resin (50% solid content) and 1% liquid paraffin as wax were applied for all boards, to enhance the dimensional stability of the panels and for an efficient press cycle. As a hardener, ammonium chloride (NH4Cl, 2%, based on the resin weight) was applied to the UF solution. The resinated particles were placed in a molding box. Furnishes were manually formed, and prepressed into 50 by 50-cm mats inside the box. The adhesive-coated mats were then compressed on steel cauls in a computer controlled press (Carver Laboratory Press), using a pressure of 5 MPa and a temperature of 140 °C for 10 min to a target thickness of 12.7 mm and two target densities of 650 and 750 kg/m^3.

A total of 72 single-layer panels, three panels for each treatment combination, from three cultivars (Barhi, Saqie, and Sukkari) of date palm, two particle sizes (sizes D and E), with or without hot water treatment, and at two density levels (650 and 750 kg/m^3) were manufactured. After pressing, the panels were trimmed to a final size of 48 by 48 cm to avoid edge effects. Particleboards were conditioned for 3 weeks in a special chamber cabinet to maintain an RH of 65% ± 3% and temperature of 20 °C ± 1 °C. The conditioned panels were cut later into various sizes for property evaluations. Mechanical properties evaluation, including modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond strength (IB), as well as the physical properties, including linear expansion (LE), thickness swelling (TS), and water absorption (WA), are the most important specifications required for particleboard evaluation. They were measured for each finished panel.

2.7. Mechanical Testing

Finished particleboards were cut into various specimens following the American Standard Testing Methods [12]. Figure 2 represents the cutting diagram for mechanical and physical samples taken from the manufactured panels. For the bending test, four rectangular (7.5 by 32-cm) pieces were used for three-point flex measurement of MOR and MOE. The mechanical properties were determined using a Universal Testing Machine (Model MTI-20K, Measurements Technology Inc., Roswell, GA, USA, equipped with 5000-kg load cell). The span of bending test samples was 28 cm with rounded supports. Samples were loaded at the center of span, and load was applied to the top surface of samples, with a uniform loading rate of 6 mm/min (as the thickness of panels was 12.7 mm). The load-deflection data were obtained until the maximum load was achieved. Both MOR and MOE were calculated from data obtained from computer software attached to the testing machine. Each reported value is an average of 12 measurements.

For internal bond test (IB), four 5 cm square pieces were used to determine the cohesion of panels. The square faces of the samples were effectively bonded with high quality adhesive to two loading blocks of steel alloy 5 cm square and 2.5 cm in thickness. The blocks were then attached to the same testing machine mentioned previously and a uniform rate of tension motion of 1 mm/min was applied. The maximum load was recorded and divided by the sample surface area (25 cm^2) to calculate the internal bond for each sample. Each reported value is an average of 12 measurements.

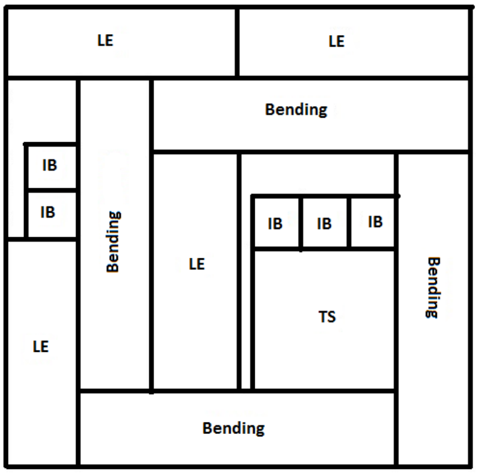

Figure 2. Cutting diagram for mechanical and physical samples taken from the manufactured panels (48 × 48 cm). Bending samples = 32 × 7.5 cm, internal bond (IB) = 5 × 5 cm, linear expansion (LE) = 24 × 7.5 cm, thickness swelling and water absorption (TS) = 15 × 15 cm.

2.8. Physical Testing

For the LE test, four rectangular 7.5 by 24-cm pieces from each panel were used for determining LE according to American Standard Testing Methods [12]. All the samples assigned for the test were conditioned for 2 weeks at an RH of 50 percent and a temperature of 20 °C ± 2 °C. Measurements of the samples' length were recorded to the nearest 0.02 mm with a digital caliper. Samples were conditioned again for 2 weeks at an RH of 90% ± 5% and a temperature of 20 °C ± 2 °C and measured again at the same previous position. The difference between the two measurements was used to calculate LE as percentages of the first conditioning values. Each reported value for LE is an average of six measurements. For the TS and WA test, one square 15 by 15-cm piece from each panel was used for determining TS and WA according to American Standard Testing Methods [12].TM Standard (ASTM D1037-2006). Samples were soaked in water at room temperature (20 °C–22 °C) for 2 and 24 h to determine the short- and long-term properties. The weight and thickness of the samples was measured before and immediately after soaking and used to calculate WA and TS, which are reported as percentages of the values before soaking. Each reported value for WA is an average of three measurements.

2.9. Statistical Analysis

Analysis of variance (ANOVA) using a four factorial experiment, with a complete randomized design (CRD), was performed by SAS software package [16]. The significance of different treatments was determined with analysis of variance and a least significant difference test (α = 0.05). The specific methods used for evaluation of various properties are described below.

3. Results and Discussion

The aim of this study was collecting the basic data for using date palm frond residues to be used in particleboard manufacture in Saudi Arabia. For this reason, all the data required about the raw material, such as chemical composition, anatomy structure, fiber length, and particle dimensions were determined. The study is also focused on evaluating the strength properties of modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond strength (IB), and responses of these boards to the linear expansion (LE) and thickness swelling (TS). This information is required prior to the commercialization of these residues as value-added products.

3.1. Particle size and Geometry

Coarse particles (0.64 mm < D < 0.25 mm) and fine particles (0.25 mm < E < 0.12 mm) used for manufacturing particleboard in this study are shown in Figure 3, and the measurements of length, width, thickness, aspect ratio (length/width), and slenderness ratio (length/thickness) are listed in Table 1.

Figure 3. Coarse and fine date palm frond particles used in this study.

It is clear from Table 1 that coarse and fine particles have average length values between 42.3 mm–48.6 mm and 42.3 mm–48.6 mm, respectively. The range value of thickness for coarse and fine particles was 0.53 mm–0.83 mm, respectively. According to these measurements, the slenderness ratio values for coarse and fine particles ranged 33.5–58.3 and 48.1–78.9, respectively. However, both particle sizes of Saqie cultivar have attained the highest slenderness ratio, recording 58.3 and 78.9 for coarse and fine particles, respectively.

Table 1. Mean values measurements of coarse and fine particles for the three date palm cultivars used in this study.

Cultivar	Size	Length (mm)	Width (mm)	Thickness (mm)	Aspect ratio	Slenderness ratio
Saqui	Coarse	48.6 (9.4)	1.9 (0.73)	0.62 (0.18)	15.6 (3.1)	58.3 (12.1)
	Fine	16.2 (6.6)	1.3 (0.72)	0.21 (0.10)	19.8 (7.1)	78.9 (19.7)
Barhi	Coarse	45.9 (11.4)	2.3 (0.82)	0.83 (0.25)	20.9 (4.8)	36.9 (15.3)
	Fine	12.8 (4.7)	1.2 (0.45)	0.28 (0.11)	12.4 (6.2)	54.6 (20.3)
Sukkari	Coarse	42.3 (11.4)	2.2 (0.82)	0.53 (0.25)	20.9 (4.8)	33.5 (12.3)
	Fine	14.8 (4.7)	1.3 (0.45)	0.22 (0.11)	13.4 (6.2)	48.1 (20.3)

Each value is an average of 150 measured particles. Values in parentheses are standard deviations.

3.2. Frond Density, Fiber Length, and Chemical Composition

It is clear from Table 2 that Saquie cultivar has recorded the highest mean values for frond density and fiber length, recording 0.73 g/cm^3 and 1.14 mm, respectively. Saquie cultivar has also recorded the highest mean values for cellulose, lignin, and extractive content, recording 48.86, 31.28 and 23.51%, respectively, while this cultivar has recorded the lowest mean value of 19.86% for hemicellullose content. More fiber length would increase the density of wood. Increasing wood density improves the mechanical properties of wood [17]. The cellulose is the main component of wood. It gives strength to wood. Low hemicellulose content decreases the water diffusion and thickness swelling. Lignin is a hydrophilic component and it shows water repellent effectiveness [17]. Larger amounts of extractives in wood cause poorer mechanical properties due to breaking down of the adhesive to fiber linkage [18]. Extractives negatively affect adhesive bonding and adhesion.

Table 2. The mean values for frond density, fiber length, and the chemical composition for the three date palm cultivars used in this study.

Frond cultivar	Biomass density (gm/cm^3)	Fiber length (mm)	Extractives content (%)	Cellulose content (%)	Hemicellulose content (%)	Lignin content (%)
Barhi	0.628 C (0.08)	1.09 AB (0.01)	19.13 B (1.8)	47.84 B (2.4)	23.10 A (1.8)	29.6
Saqie	0.731 A (0.05)	1.14 A (0.02)	23.51 A (1.7)	48.86 A (2.1)	19.86 C (1.3)	31.28
Sukkari	0.683 B (0.05)	1.06 B (0.01)	22.64 A (1.6)	47.17 A (1.3)	22.30 B (1.9)	30.19
L.S.D$_{0.05}$	0.040	0.06	0.065	0.77	2.26	----

Values in parentheses are standard deviations.

3.3. Date Palm Anatomy

Regarding the frond anatomy, sections were prepared to evaluate the anatomical structure of the different cultivars using a light microscope. Figure 4 illustrates the typical cross section taken from the basal frond segments of A: Barhi, B:Sukkari, and C: Saquie cultivars, respectively, showing the variation in size of vascular bundles rich in fibers embedded in the parenchymatous tissues. However, it can be noticed that there are three zones of vascular bundles which can be distinguished across the midrib, the peripheral, transitional zone, and inner zone. In the first and second zones, the fiber sheath is thick and the vascular bundles are numerous, with small parenchyma cells between them. The third zone is the broadest, where the bundles reach their highest diameter. Fiber tissue percent is higher in the periphery and transition zones (38%) than in the inner or central zone (10%). The size and shape of fiber strands in the vascular bundle are the most important structural factor that determines the date palm leaves' behavior. The periphery and transition zone across the midrib, which is characterized by the higher percentage of fiber tissue and larger number of bundles, affects the density and strength properties of the frond. Generally, as shown in Figure 3 Saqie cultivar was found to be superior on account of having the highest number of vascular bundles per cm^2 cross-sectional area (205), and a higher fiber transverse wall area fraction (22%) and a narrow vessel diameter (55.42 μm).

More fiber length and a higher number of cells increase the density of wood. Increasing wood density improves the mechanical properties of wood [10,19]. Bhat *et al.* [20] mentioned that the average fiber length of the date palm midrib is within the average of dicotyledons and hardwood species and shorter than the fiber length of stems of some other palm species.

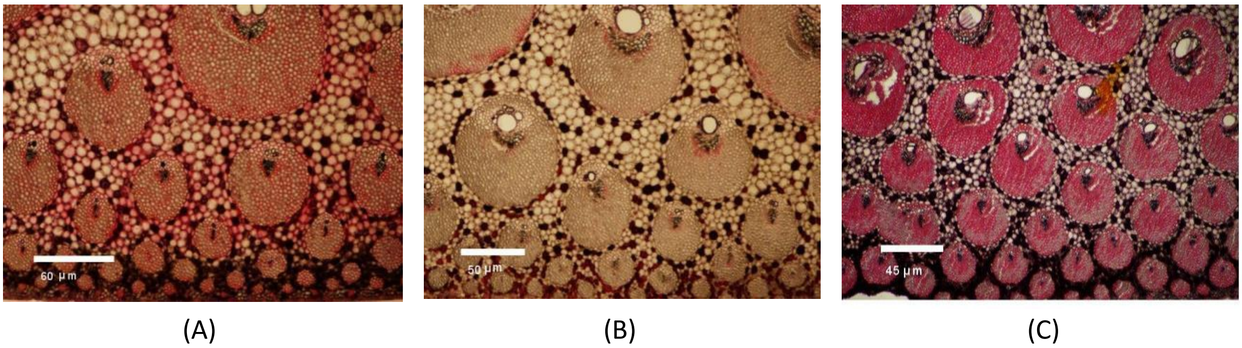

Figure 4. Cross section of fronds of the basal segment of (**A**) Barhi, (**B**) Sukkari and (**C**) Saquie cultivars passing from the peripheral region, showing varying sizes of vascular bundles rich in fibers embedded in the parenchymatous tissues.

3.4. Effects of Individual Parameters

Table 3 summarizes the F-values (as an indicator for parameter significance) obtained from the statistical analysis and the ANOVA results for the effects of date palm cultivar, particle size, water treatment, and panel density on both mechanical properties (MOR, MOE and IB) and dimensional stability properties (LE, TS and WA) for all panel combinations under investigation. It is clear that **date palm cultivar** has a significant effect on all the mechanical and dimensional stability properties under this study, while **particle size** has a significant effect only on MOR, IB and LE. **Hot water extraction** treatment has also a significant effect on all dimensional stability properties and MOE, while **panel density** has a significant effect on all mechanical properties as well as LE (Table 3). The mean values for each individual parameter of date palm cultivars, particle size, water extraction treatments, and panel densities on both the mechanical and dimensional stability properties are represented through Figures 5–9.

Table 3. F-values obtained from the statistical analysis and the ANOVA results for the main effects as well as the interactions of date palm cultivar, particle size, water treatment, and panel density on both mechanical properties and dimensional stability properties.

Parameters	MOR	MOE	IB	LE	2 h-TS	2 h-WA	24 h-TS	24 h-WA
Cult	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P = 0.0004$	$P = 0.0012$	$P < 0.0001$	$P = 0.0003$	$P < 0.0001$
Size	$P < 0.0001$	$P = 0.1596$	$P < 0.0001$	$P < 0.0001$	$P = 0.0294$	$P = 0.8766$	$P = 0.1325$	$P = 0.1686$
Cult × Size	$P = 0.3286$	$P = 0.0907$	$P = 0.0381$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
Wt	$P = 0.7550$	$P = 0.0013$	$P = 0.8087$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
Cult × Wt	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
Size × Wt	$P = 0.0016$	$P = 0.0781$	$P < 0.0001$	$P < 0.0001$	$P = 0.4749$	$P < 0.0001$	$P = 0.0059$	$P = 0.0061$
Cult × Size × Wt	$P = 0.0572$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
D	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P = 0.0898$	$P = 0.4883$	$P < 0.0005$	$P = 0.4142$
Cult × D	$P < 0.0001$	$P = 0.1669$	$P < 0.0001$	$P = 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
Size × D	$P = 0.9588$	$P = 0.8872$	$P = 0.0110$	$P = 0.0006$	$P = 0.0487$	$P = 0.8469$	$P < 0.0001$	$P = 0.3242$
Cult × Size × D	$P = 0.0122$	$P = 0.2434$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
Wt × D	$P = 0.7867$	$P = 0.1432$	$P = 0.0007$	$P < 0.0001$	$P = 0.0058$	$P = 0.1165$	$P = 0.0001$	$P = 0.1034$
Cult × Wt × D	$P = 0.6051$	$P = 0.2311$	$P < 0.0001$	$P = 0.0329$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P = 0.0156$
Size × Wt × D	$P = 0.4103$	$P = 0.5799$	$P = 0.0003$	$P = 0.5833$	$P < 0.0001$	$P = 0.0426$	$P < 0.0001$	$P = 0.0019$
Cult × Size × Wt × D	$P = 0.0422$	$P = 0.3177$	$P < 0.0001$	$P = 0.0035$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$

Abbreviations: Cult = date cultivar, Size = particle size, Wt = water treatment, and D = panel density.

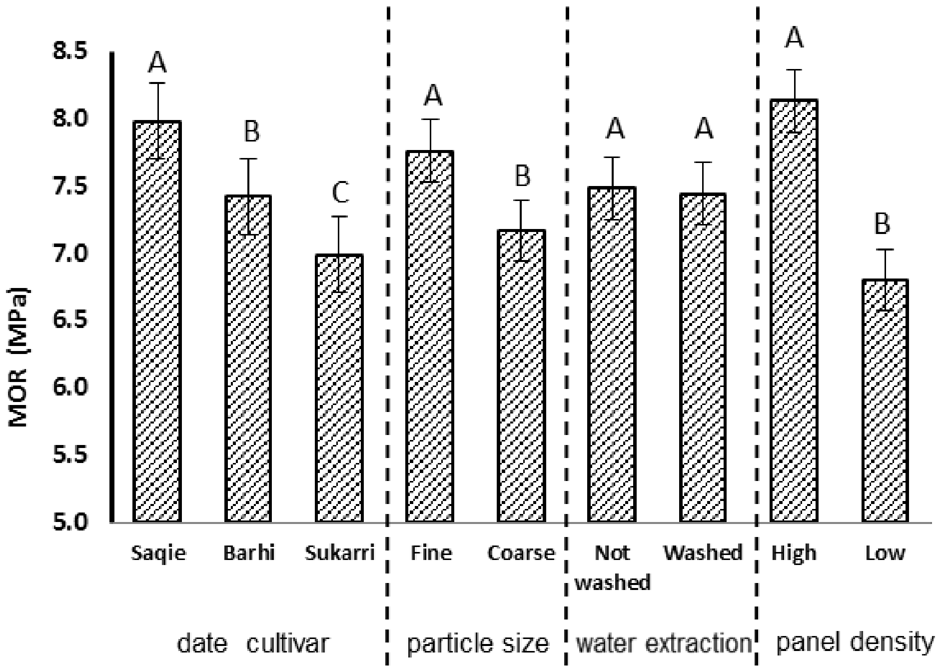

Figure 5. Effect of date palm cultivar, particle size, hot water extraction, and panel density on Modulus of Rupture (MOR) property. (Means with same letter do not significantly different at L.S.D.$_{0.05}$).

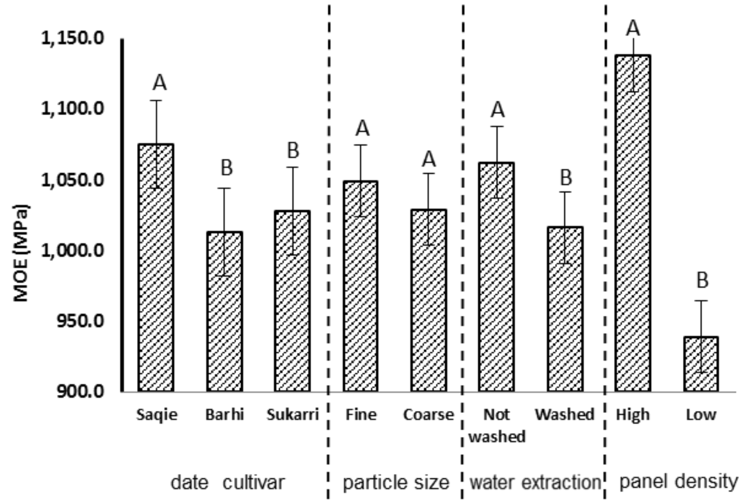

Figure 6. Effect of date palm cultivar, particle size, hot water extraction and panel density on Modulus of Elasticity (MOE) property. (Means with same letter do not significantly different at L.S.D.$_{0.05}$).

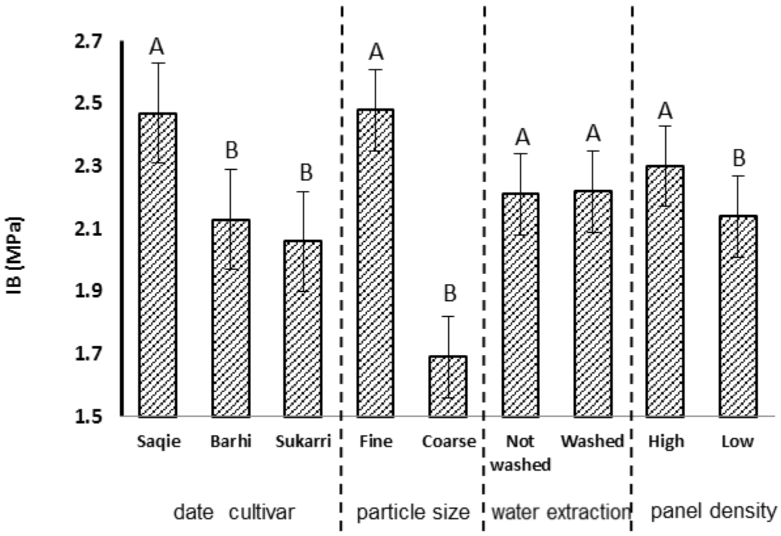

Figure 7. Effect of date palm cultivar, particle size, hot water extraction and panel density on internal bond (IB) property. (Means with same letter do not significantly different at L.S.D.$_{0.05}$).

3.5. Effect of Panel Density

As the board density increased, the compaction ratio increased providing a higher contact surface between the particles, and more efficient glue bonds were improved compared to lower compaction ratio. This caused higher flexural properties and internal bond [10,19,21]. This conclusion obviously applies to our experiment (Figures 5–9), where increasing board density resulted in an increase in all properties except 24h-TS. High density panels of 750 kg/m^3 have recorded higher mean values for MOR, MOE, and IB, recording mean values of 8.13, 1138, and 2.3 MPa, respectively. Low density panels (650 kg/m^3) have recorded lower mean values (better performance) for LE property, recording 0.147%.

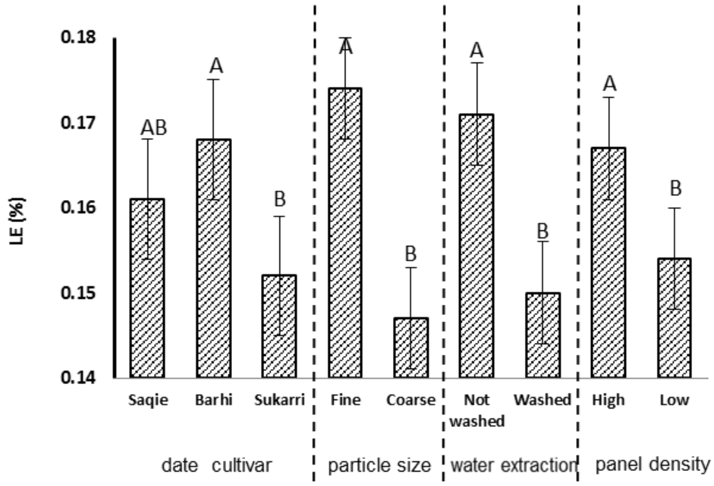

Figure 8. Effect of date palm cultivar, particle size, hot water extraction and panel density on linear expansion (LE) property. (Means with same letter do not significantly different at L.S.D.$_{0.05}$).

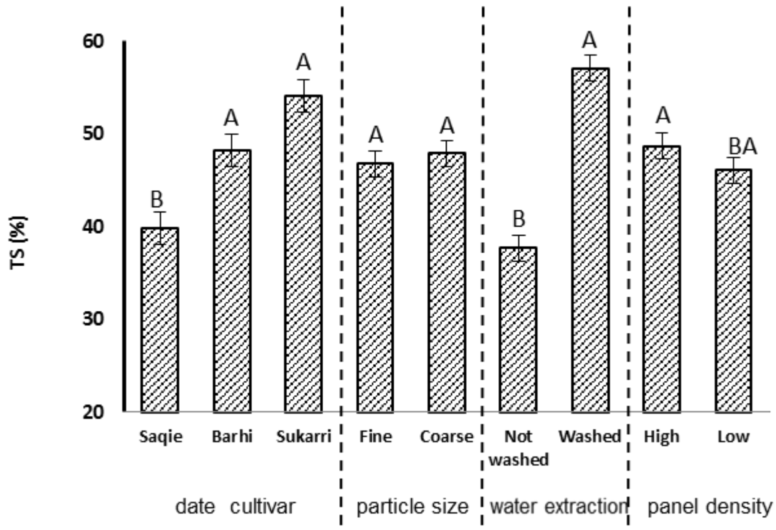

Figure 9. Effect of date palm cultivar, particle size, hot water extraction and panel density on thickness swelling (24-h TS) property. (Means followed by with same letter do not significantly different at L.S.D.$_{0.05}$).

3.6. Effect of Particle Size and Shape

The fine particles resulted in higher mean values than coarse ones for MOR, MOE, IB, and LE, recording 7.76, 1049, 2.48 MPa, and 0.174%; respectively, while particle size had no effect on 24 h-TS property (Figures 5–9). The higher strength values for the fine particles may be attributed to the higher slenderness ratio recorded by the fine particles compared to the coarse ones, as shown in Table 1. The fine particles had slenderness mean values of 78.9, 54.6, and 48.1 for Saqie, Barhi, and Sukkari cultivars, respectively, while for coarse particles these values were 58.3, 36.9, and 33.5, respectively, at the same order. Our results were supported by Biswas *et al.* [22], as they mentioned that properties of particleboards could be affected significantly by particle geometry, which includes the shape and particle size. Particle size is one of the factors that can be manipulated to improve the physical and mechanical properties of particleboard. Increasing the length of particles and the slenderness ratio (length/thickness) also increases both MOR and MOE, but decreases the IB [23]. Osarenmwinda and Nwachukwu [24] also reported that the longer particle size gave better mechanical properties of the particleboard, while Ngueho Yemele *et al*. [25] mentioned that IB strength mostly increased with decreasing particle size. However, thicker and shorter particles have a higher specific surface area, and they receive more resin and provide better inter-particle contacts, which may improve IB property.

Regarding the effect of particle size on dimensional stability properties, Viswanathan and Kailappan [26] reported that WA and TS were least for the board made from the largest particles. They explained that the higher WA values attained by the boards made from smaller particles would be because of the larger surface area, which absorbs more water. However**,** the high values for both WA and TS recorded in our study may be due to the fact that date palms are monocotyledons, and there are huge amounts of parenchymatous tissues around the vascular bundles, which might absorb more water than the wood inside the vascular bundles as shown in Figure 4.

3.7. Effect of Hot Water Extraction

The extracted particles with hot water have significantly lower mean value for LE property than the un-extracted ones, recording 0.15%, while the un-extracted ones have recorded significantly higher mean values for MOE and lower mean value for 24h-TS compared with the extracted particles, recording 1062 MPa and 37.7%, respectively. On the other hand, water treatments have no effect on both MOR and IB properties (Figures 5–9). However, the affinity of particleboard to water is one of the main limitations for using these panels in moisture-rich environments. Dimensional stability and durability can be improved by hot water extraction, which increases panels resistance to moisture uptake and it does not need additional chemicals [27]. Hot water extraction is an autocatalytic thermo-chemical process for fractionation of easily accessible sugars in lignocellulosic biomass [28]. Sweet and Winandy [29] found a negative effect of hemicellulose reduction on the wood's mechanical properties after such treatment. It is a fact that some of the extractives and starch content are eliminated during the washing process of the particles, resulting in a negative impact on the mechanical properties. The amount of extractives content in date palm cultivars as shown in Table 2 was about 19.1%–23.5%, which is considered a relatively high percentage compared to wood. Similar findings were also determined in a past study [30]. Particleboard made from date palm treated with hot water extraction had lower bending values than those made from unwashed control panels [31].

3.8. Effect of Date Palm Cultivar

Saqie cultivar has significantly recorded the highest mean values for MOR, MOE, and IB, recording 7.98, 1075, and 2.47 MPa, respectively, and has recorded the lowest mean value (more dimensionally stable) for 24h-TS recording 39.8%. On the other hand, Sukkari cultivar has recorded the lowest mean value of 0.15% for LE property.

3.9. The Combined Effect of All Parameters on Mechanical Properties

Table 4 displays the average values of the mechanical properties of the panel samples as they were affected by the above-mentioned four parameters. The highest MOR value of 9.82 MPa was recorded by the panels made from the un-extracted fine particles from Barhi cultivar at the 750 kg/m^3 density level, while the highest MOE value of 1245.4 MPa was recorded by the panels made from the un-extracted fine particles from Saqie cultivar at the 750 kg/m^3 density level. The highest IB value of 3.62 MPa was recorded by the panels made from the extracted fine particles from Saqie cultivar at the 750 kg/m^3 density level.

However, it seems that high density panels with fine particles of Saqie cultivar for both water treatments have obtained the best parameters combination for achieving higher mechanical properties in our study, recording MOR mean values of 9.11 and 9.03 MPa, MOE values of 1130 and 1245 MPa, and IB values of 3.62 and 2.43 MPa for extracted and un-extracted particles, respectively. Conversely, the lowest mean values for MOR, MOE, and IB were 5.06, 800 MPa, and 0.67 MPa, respectively for panels made from coarse un-extracted particles of Barhi cultivar at low density level.

Generally, Table 4 made it clear that manufacturing high density panels at 750 kg/m^3 using fine date palm particles have obtained better values for MOR, MOE, and IB properties compared to the low density panels using coarse particles manufactured under our investigation, while Saqie frond cultivar has achieved better performance for the same previous properties compared to the other two cultivars of Barhi and Sukkari. There are many reasons for the better results of Suqie cultivar such as higher values for frond density, fiber length, and particle slenderness ratio. Saquie cultivar has also had the highest values for cellulose, lignin, and extractive content, and the lowest value for hemicellullose content, as well as having the highest number of vascular bundles per cm^2 cross sectional area.

The American National Standards (ANSI A208.1-2009) [32] stated that the minimum requirements for MOR, MOE, and IB were 10, 1550, and 0.36 MPa, respectively, for commercial particleboard (Grade M1), and were13, 2000, and 0.4 MPa, respectively, at the same order, for the industrial particleboard (Grade M2). However, all the MOR and MOE values found in this study were lower than those stated in ANSI standards for both M1 and M2 grades, but at least 25% of the samples satisfied the minimum MOR limit of 8.0 MPa for particleboard (Type 8) for Japanese industrial standards [33]. On the other hand, all of IB samples have satisfied both the American and Japanese standards [32,33].

3.10. The Combined Effect of all Parameters on Dimensional Stability Properties

Table 4 displays the average values of dimensional stability properties of the panel samples (LE, TS and WA) for the panels under investigation. The lowest LE value of 0.09% was recorded by the panels made from the extracted coarse particles of Saqie cultivar at the 0.65 g/cm^3 density level, while the LE range values was 11%–23% for all other panel combinations. However, all the LE values tabulated in this study were lower than those stated in ANSI requirements [32] for both M1 and M2 grades (<0.40%). Generally, within each cultivar, we could say that low density panels at 650 kg/m^3 with hot water treated coarse particles have obtained lower values for LE property compared to the high density panels with fine particles manufactured under our investigation, In addition, Miyamoto *et al.* [23] mentioned that LE of particleboard decreased with increasing particle length and size.

Table 4. Average values of mechanical and dimensional stability properties of manufactured panels.

Cultivar	Particle Size	Water Extraction	Target Density (g/cm^3)	Actual Density (g/cm^3)	Mechanical Properties			Dimensional Stability Properties				
					MOR (MPa)	MOE (MPa)	IB (MPa)	2-h. TS (%)	2-h. WA (%)	24-h. TS (%)	24-h. WA (%)	LE (%)
Barhi	Fine	Extracted	0.65	0.67	6.2 (1.1)	874 (78)	2.61 (0.27)	41.6 (2.4)	83.2 (4.5)	46.0 (2.3)	104.6 (2.8)	0.12 (0.02)
			0.75	0.72	7.8 (0.5)	1071 (98)	2.56 (0.38)	31.5 (13.8)	79.0 (4.7)	46.4 (2.2)	104.5 (5.1)	0.14 (0.02)
		Un-extracted	0.65	0.66	7.5 (0.8)	949 (79)	2.12 (0.22)	29.3 (1.2)	61.4 (5.2)	34.9 (0.8)	86.9 (4.6)	0.18 (0.03)
			0.75	0.74	9.8 (0.7)	1178 (66)	2.52 (0.39)	27.5 (1.6)	51.2 (2.2)	36.4 (1.9)	79.1 (2.9)	0.22 (0.03)
	Coarse	Extracted	0.65	0.66	5.1(0.7)	800 (63)	0.67(0.17)	80.0 (8.6)	102.4 (12)	98.6 (8.8)	133.5(11.9)	0.23(0.03)
			0.75	0.72	7.9 (0.9)	1018 (120)	1.78 (0.32)	43.7 (4.7)	77.3 (4.9)	51.8 (5.8)	103.3 (5.3)	0.19 (0.02)
		Un-extracted	0.65	0.67	6.2 (0.8)	958 (101)	2.46 (0.38)	23.8 (1.5)	56.7(2.9)	32.1(1.0)	82.4 (2.7)	0.12(0.03)
			0.75	0.74	8.8 (1.3)	1218 (154)	2.31(0.29)	29.7 (2.8)	52.5(2.4)	40.0 (1.5)	78.5 (2.5)	0.15 (0.03)
Saqie	Fine	Extracted	0.65	0.69	7.5 (1)	986 (84)	2.40 (0.32)	38.8 (1.6)	82.4 (3.7)	44.2 (1.6)	107.1 (2.5)	0.19 (0.03)
			0.75	0.73	9.2 (0.9)	1130 (75)	3.62 (0.38)	31.7 (1.8)	49.7 (11)	42.0 (3.7)	81.3 (16.9)	0.22 (0.02)
		Un-washed	0.65	0.67	7.4 (1.1)	1055 (120)	2.38 (0.36)	24.7 (5.0)	46.8 (9.5)	33.5 (2.9)	82.8 (2.2)	0.13(0.03)
			0.75	0.74	9.0 (1.23)	1245 (109)	2.43 (0.30)	27.7 (1.1)	55.4 (2.9)	36.1 (1.0)	82.6 (0.9)	0.16 (0.02)
	Coarse	Extracted	0.65	0.68	8.2 (0.7)	975 (111)	2.41(0.26)	33.1(1.9)	70.8 (8.2)	40.9 (1.6)	94.9 (6.3)	0.09 (0.02)
			0.75	0.72	8.9 (1.5)	1213 (151)	2.33(0.24)	42.1(1.5)	77.9 (4.9)	49.1 (1.7)	102.1(4.5)	0.11 (0.02)
		Un-extracted	0.65	0.68	6.5 (0.5)	924 (78)	2.16 (0.30)	26.8 (0.6)	62.5 (3.4)	33.3 (1.5)	83.6 (4.5)	0.14 (0.03)
			0.75	0.71	7.2 (0.8)	1071 (84)	2.01 (0.21)	31.4 (2.9)	64.9 (7.4)	39.0 (3.4)	87.0 (7.2)	0.18 (0.03)
Sukkari	Fine	Extracted	0.65	0.66	6.8 (0.6)	925 (51)	2.32 (0.28)	51.3 (0.7)	96.9 (3.2)	66.7 (3.7)	125.0 (2.0)	0.16 (0.02)
			0.75	0.72	7.8 (1.1)	1098 (155)	1.89 (0.17)	84.8 (0.5)	133.7 (3.1)	100.2 (3.5)	158.1 (3.6)	0.11 (0.02)
		Un-extracted	0.65	0.68	7.2 (0.9)	909 (98)	2.25(0.33)	29.2 (1.2)	70.7 (0.2)	35.9 (0.3)	93.1(0.3)	0.23 (0.01)
			0.75	0.71	6.9 (1.3)	1160 (94)	2.60 (0.24)	23.5 (1.8)	68.4 (2.6)	39.6 (1.5)	95.3 (3.3)	0.22 (0.03)
	Coarse	Extracted	0.65	0.67	7.0 (0.8)	993 (121)	2.06 (0.13)	42.3(3.09)	81.6 (4.9)	47.0 (3.3)	108.4 (5.5)	0.11 (0.02)
			0.75	0.71	7.1 (0.8)	1103 (15)	2.03 (0.18)	46.9 (0.9)	81.8 (4.5)	52.3 (0.5)	104.0 (4.6)	0.14 (0.02)
		Un-extracted	0.65	0.61	6.1(1.3)	919 (150)	1.82 (0.22)	32.4 (0.8)	71.8 (0.9)	39.3 (1.3)	93.4 (1.0)	0.15 (0.02)
			0.75	0.72	7.0 (1.0)	1117 (87)	1.48 (0.21)	43.1 (0.7)	84.5 (2.4)	51.6 (1.7)	106.6 (2.0)	0.17 (0.02)
		L.S.D.$_{0.05}$			0.79	8.2	0.26	6.43	9.01	4.96	9.27	0.02
ANSI standard		M1 commercial panels			10	1550	0.36	....	....	....	....	0.40%
		M2 industrial panels			13	2000	0.40	....	....	....	....	0.40%
CEN standard					....	....	....	8%	....	15%	....	....
JIS Type 8					8	2000	....	....	....	....	....	....

Numbers in parentheses are standard deviation values. ANSI: American National Standards Institute, CEN: European Committee for Standardization, JIS: Japanese industrial standards.

Regarding the thickness swelling test (TS), the 2h-TS samples have recorded range values of 23.8%–84.0% for all panels, while the range values for 24h-WA was 32.1%–100.3%. On the other hand, for water absorption test (WA), the 2h-WA samples have recorded range values of 46.8%–102.4% for all panels, while the range values for 24h-WA was 78.5%–158.2%. Based on European Committee for Standardization (CEN) [34], particleboard should have a maximum thickness swelling value of 8% and 15%, for 2-h and 24-h immersion,; respectively.

In general, the observed TS and water WA values for particleboards in our study were too much higher than 15% (as a maximum requirement). Similar high TS values have been reported for the particleboards that were produced using agricultural residues, such as 60.7% for tobacco and tea leaves [35], 35% for cotton stalks [36], and 19.6% for hazelnut hulls [37], after 24h water soaking. Many treatments could be utilized in the particleboard production to improve these properties, such as the use of phenolic resins, coating the particleboard surfaces, and acetylating of particles to improve the water repellency of the panels [38–40].

3.11. Mechanical Properties of Date Palm in the Literature

Regarding to the mechanical properties published in the past few years for date palm frond, El-Mously *et al*. [8] obtained MOR, MOE, and IB values of 10.5, 18,512, and 0.43 MPa, respectively, for board density of 650 kg/m^3, while Nemli *et al.* [41] obtained MOR values in the range of 15.3–18.9 MPa and IB values in the range of 0.35–0.83 MPa for the same density. On the other hand, Ashori and Nourbakhsh [42], using a board density of 750 kg/m^3 and resin content between 9 and 11 percent, attained MOR, MOE, and IB range values of 10–16.6 MPa, 1333–1861 MPa, and 0.38–0.63 MPa, respectively. Hegazy and Aref [10], using a laboratory hammer mill, mentioned MOR, MOE, and IB values of 13.3, 2018, and 0.53 MPa, respectively, for a panel density of 790 kg/m^3, while they got 9.04, 1443, and 0.43 MPa, respectively, for a panel density of 670 kg/m^3. Lower bending properties of the samples made in this work could be related to the particles configuration as a result of the flaking machine and the substantial amount of parenchyma cells and non-fibrous structure of the frond particles, which was observed during microscopic evaluation of the sections taken from the samples, where walls of the parenchyma cells is thin, in contrast to the thick cell wall of fibers. Hashim *et al.* [43] and Wazzan [44] revealed similar findings in a past investigation related to particleboard panels manufactured from oil palm fronds. Usually, boards having the lower mechanical properties can be used as insulating material in buildings because such boards would not be subjected to any mechanical stress or mechanical properties.

4. Conclusions

1. This study showed that raw material from date palm fronds has the potential to be used in the manufacture of experimental particleboard panels.
2. Increasing board density would increase all mechanical properties by providing a higher contact surface between the particles and more efficient glue bonds.
3. The internal bond strength of the samples was found to be satisfactory, but the bending properties of the samples need to be improved using different approaches, including higher resin distribution or modifying the particle size.

4. Better results for all mechanical properties could be obtained when both parameters of Saqie cultivar and fine particles were used.
5. Hot water treatments have no effect on both MOR and IB properties, but improved the LE performance.

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Author Contributions

Said S. Hegazy conducted the panel manufacturing, physical testing, collection of data, data analysis, writing of the final paper, and preparation of figures and graphs. Khaled Ahmed conducted the mechanical testing. All authors read and approved the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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