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Chapter

Processing and Properties of Oil Palm Fronds Composite Boards from *Elaeis guineensis*

*Razak Wahab, Mohd Sukhairi Mat Rasat,
Norashikin Mohd Fauzi, Mohamad Saiful Sulaiman,
Hashim W. Samsi, Nasihah Mokhtar,
Ros Syazmini Mohd Ghani and Muhammad Haziq Razak*

Abstract

Oil palm fronds are one of the biomass residues originating from oil palm plantations. It has great potential to be used as an alternative material for the composite boards industry to reduce dependency on wood-based raw materials. The fronds are obtainable all the year round and in big quantity. The oil palm fronds had been processed as compressed oil palm fronds to form such a potential composite board in this topic. A composite board from compressed oil palm fronds was produced by removing the fronds' leaflets and epidermis. The sample was sliced longitudinally into thin layers and compressed into an identical thickness at about 2 to 3 mm. Pieces of the sample were dry using the air-dried method. They were then mixed with phenol and urea-formaldehyde of resins in the range of 12-15% and compressed again with another layer forming a composite board. Standard outlined by the International Organization for Standardization (ISO) tested for their physical and strength properties of composite board. Found that the physical and strength aspects' properties show that the composite board possessed characteristics at par or equivalent. The composite board from compressed oil palm fronds has good prospects to be used as an alternative to wood. Thus, this characteristics can overcome the shortage in materials supply in the wood-based industry.

Keywords: Oil Plam Fronds, Anatomy Characteristics, Chemical Compsoitions, Physical & Mechanical Properties, Composite Panel

1. Introduction

Oil palm seems like another promising alternative to reduce the dependency on timber since there are plenty of oil palms in Malaysia's plantation and have high potential to be future composite boards through their residues. Agricultural fibre, especially oil palm fronds used, can be easily crushed and may be used as substitutes for wood-based raw materials. Explore the use of local natural fibre for composite boards and has an excellent potential to compete with other commercial products. The oil palm fronds are usually left rotting between the rows of palm trees. This method served mainly for soil conservation, erosion control, and ultimately the long-term benefit of nutrient recycling [1, 2].

Many studies on the oil palm fronds showed the potential of utilizing this agricultural residue for several types of value-added products. The value-added products are the manufacturing of pulp and paper, animal feed, and fibreboard in the wood-based industry [3–5]. Intensive research work is ongoing using various technologies to convert oil palm fronds for the manufacture of commercially viable composite board products [6–9]. They were chosen because they are residues and abundant in oil palm plantations. It will optimize the uses of biomass by-products, especially from oil palm fronds. Moreover, it gives better understanding and knowledge of non-wood material for future sustainability.

Currently, there is a limited supply of timber in the wood industry to cater to permanent structural use. This issue is due to poor and inconsistent quality, high and fluctuating costs associated with the supply shortage [10]. Due to the depletion of forest resources, there is a shortage of wood suppliers required by the industry. It is not surprising that alternative bio-materials are getting popular in reducing the over-dependence on the local timber industry. Furthermore, previous researchers worldwide seem to focus more on woody plants, and they paid less attention to non-woody plants. For some reason, there is a need to expand the knowledge to non-wood properties.

Additionally, the use of these oil palm fronds still lacks its contribution to commercializing [11]. Simultaneously, by maximizing the knowledge, especially on oil palm crops, the world will know that Malaysia is taking seriously in minimizing the effect of agricultural residues on the environment and reducing the consumption of natural forest. It should be done as Malaysia complained about foreign countries because of its mass production of palm oil, and Malaysia is known as the largest producer in the palm oil industry. Novel technologies with improved efficiencies and reduced environmental impacts need to be established timely to utilize a large amount of waste [12].

2. Oil palm fronds

Oil palm fronds are considered to be one of the most abundant agricultural by-products in Malaysia. Oil palm fronds are currently considered waste from oil palm plantations, and their biomass is not used entirely. In Malaysia, the total production of these felled and pruned oil palm fronds is estimated at 24.4 million mt dry matter per year [13], and this was almost doubled within a decade to about 40 million mt in 2004. Recycling is needed to produce something that can be used and avoid the pollution of the environment. Pruning activities of these oil palm fronds will be made from time to time depending on the individuals who manage them and the available quantity of oil palm fronds. The available amount is depending on the age of the oil palm tree. It is estimated that about 10,400 kg/ha of oil palm fronds can be produced yearly [14]. Meanwhile, about 14,500 kg/ha of oil palm fronds are produced by replanting activity annually [15].

The average economic life span of the oil palm is 25 years [16] and generally was replaced after 25 to 30 years [6, 17]. Oil palm mass cultivation began in 1960 [18]. The years 1990 and beyond marked a peak in the replanting of the oil palm trees. This information presents an excellent opportunity to harness the lignocellulosic biomass or by-products of the oil palm, including the fronds. Oil palm fronds are available throughout the year when the oil palms are pruned during the harvesting of fresh fruit bunches for palm oil production. Besides, many fronds are produced by replanting each year, making these fronds show an up-and-coming source for composite panels and ensuring their abundance and availability.

The oil palm trees are typically planted about 145 oil palm trees per ha. People can harvest about 25 pieces of fronds from a single palm tree roughly. Each frond weighs about 8 kg [19]. This frond weighs resulted in about 200 kg of fronds that can be obtained in a year. Malaysia can produce about 30 tons of frond biomass in 1 ha in a year. Other reviews show that under standard practice, around two palms are pruned per palm per month. Under the current plantation system in Malaysia, the oil palm density per ha is about 136 palm trees per ha. Therefore, this would yield at least 3200 pruned fronds per ha per year, yielding at least 18 mt of fronds biomass per year [20].

Oil palm fronds have great potential for use as a roughage source or as a component in compound feed for ruminants, either fresh or processed as silage or pellet [1]. This is because oil palm fronds contain the right level of nutrients, which is 70%, and the rest is carbohydrate content [21]. According to the Husin et al. [22], for soil conservation, increase fertility, improve the amount of water retention in the ground, erosion control and provide a source of nutrient to the growing oil palm trees, the fronds were left to rot in between the row of oil palm trees in the plantation. Oil palms by-products are available in a large quantity sufficient for industrial raw materials in agro-based industries. The endless and consistent supply of lignocellulosic materials from the oil palm industry, especially oil palm fronds, should be considered as new bio-resources. New product development from oil palm is now at their stage of research to be developed later on.

3. Properties of oil palm fronds

The fronds are found around the trunk in two spirals which are left-handed or right-handed. Individual mature frond has rachis, leaflets, and thorns [23]. Oil palm fronds, the aerial part of the oil palm tree comprises two central portions; they are the petiole and the leaflet. The petiole, which is the woody part of the frond, represents more than 70% of the whole frond, whereas the weight of the leaflet is less than 30%. Therefore, the proportion of petiole and leaflet portions, which is determined by the age of the frond at the time of harvest, would be the dominant factor determining the fibre composition of maturing oil palm fronds [24].

The moisture content of oil palm fronds is very high, up to 60% on a wet basis. The leaves are found at the top of the plant arranged like a crown containing 40 or more fronds. Each palm frond has 20 to over 150 pairs of roughly 2.5 cm wide leaflets arranged in two rows along each side of the petiole [25]. The frond lengths decrease from the bottom to the top level of the crown, reaching the length of about 4 m. In a cross-section, the frond shows a triangle shape with the width decreasing from the base to the end of the petiole and from the bottom to the top fronds [23]. A fruiting branch that contains thousands of fruits is held in the axils of the leaves and arranged in a rosette pattern around the crown [26, 27].

3.1 Anatomical characteristics of oil palm fronds

Anatomical characteristics of oil palm fronds are different from other woody structures in that they have four essential cell elements: parenchyma, vascular bundles, sclerenchyma, and epidermis [17]. Oil palm fronds do not possess cambium, sapwood, heartwood, and growth ring; hence their 'wood' is the primary tissue itself [28]. The fronds are primarily composed of parenchymatous tissues with numerous fibrous strands and vascular bundles. The oil palm fronds consist of a mass of discrete vascular bundles embedded in parenchymatous tissues [29]. The growth and increase of the fronds result from the overall cell division and cell

enlargement in the parenchymatous tissues, together with the enlargement of the fibre of the vascular bundles [30].

Like other monocotyledon plants, oil palm has inner and outer vascular bundles, and the same goes for its fronds. The outer region of living tissues is differentiated into a narrow cortex from the wide central cylinder. **Figure 1** shows the anatomical characteristics of the oil palm fronds. In the cylinder, vascular bundles were found concentrated at the outer and scattered at the inner division. The distribution of the vascular bundles throughout the fronds has become an essential factor influencing the oil palm fronds' anatomical features and physical properties [30]. **Figure 2** shows the oil palm fronds in the transverse section. The morphological of oil palm frond structures presented in **Figures 3–5** were observed under high-performance microscopy with different magnification.

The parenchymatous tissues comprise a short chain of polysaccharides, starch, and also a soft structure. However, the fibrous strands are principally dense cellulose which is challenging to degrade. A study found the weight ratio of the parenchymatous tissues on fibre strands in the range 24-29% to 71-76%. The riches of starch discovered in the parenchyma structure are about 55% while 2.4% in the fibre. Then, the lignin content recorded a slightly comparable value, 20% in fibre and 15.7% in the parenchyma [31]. Furthermore, regarding the orientation of

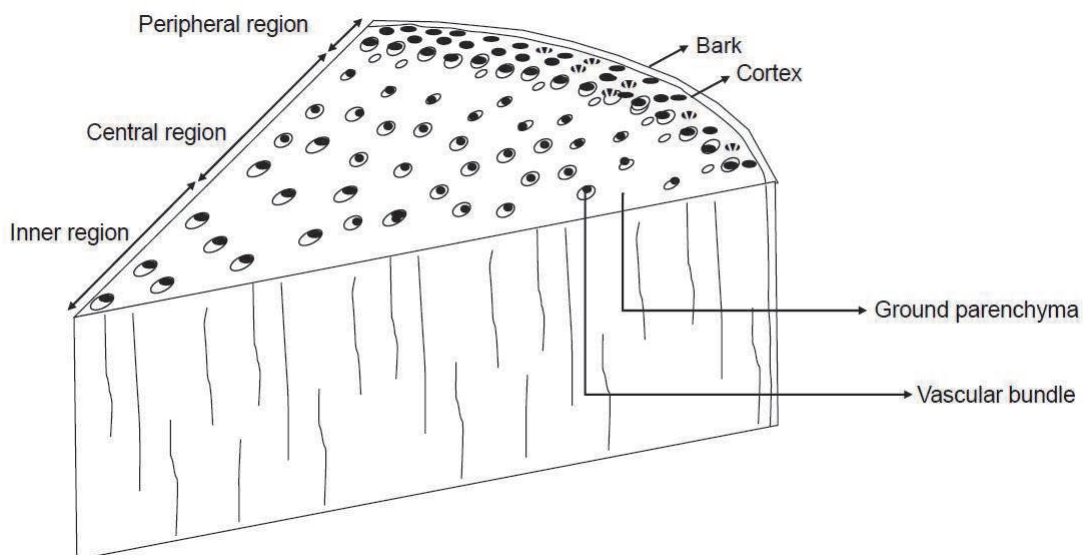


Figure 1.
Structure of anatomical characteristics of oil palm fronds.

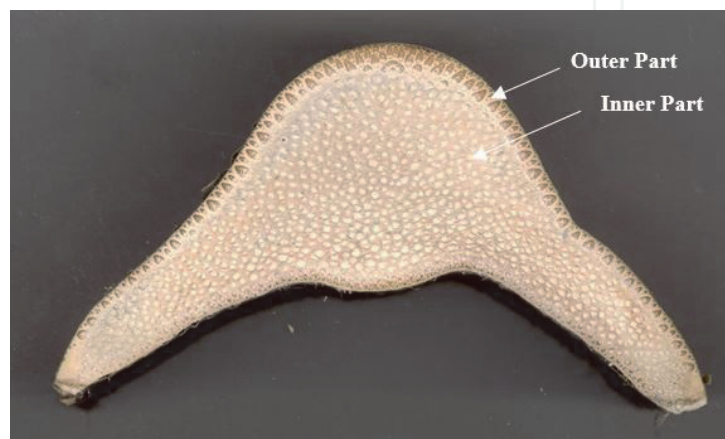


Figure 2.
Oil palm fronds at the transverse sectional view.

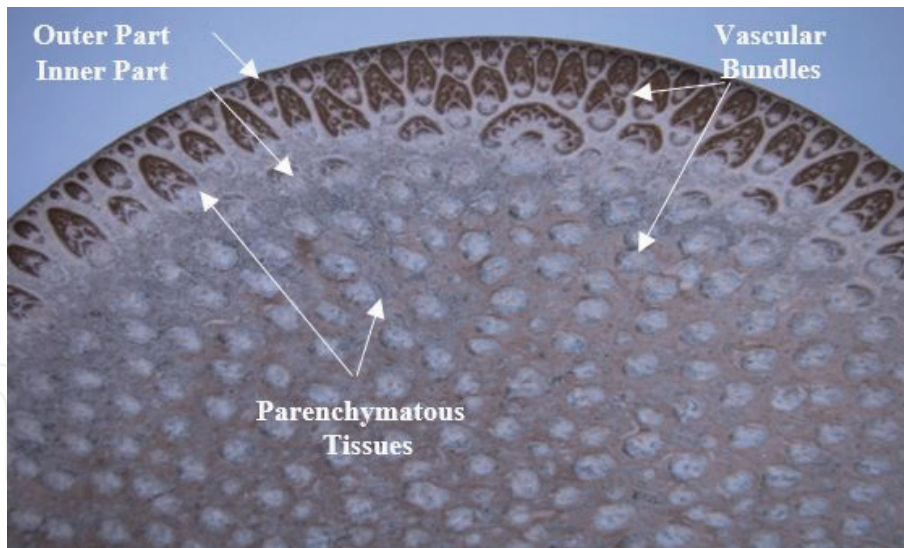


Figure 3.
High-performance micrograph of oil palm fronds at the transverse sectional view (0.75 × magnification).

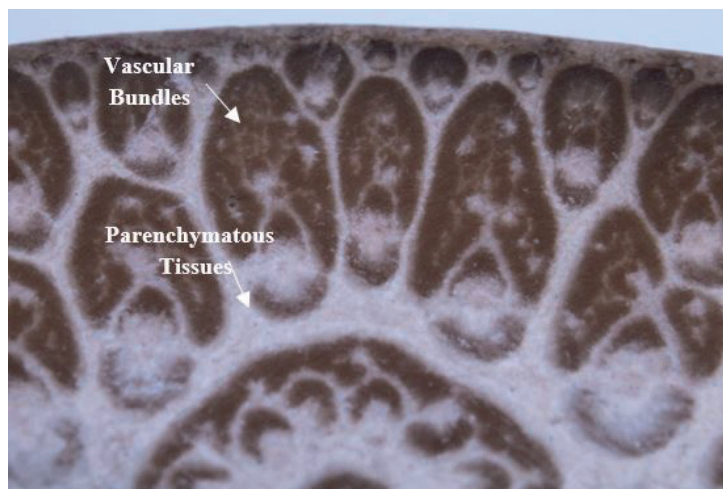


Figure 4.
High-performance micrograph of outer part on oil palm fronds at the transverse sectional view (4 × magnification).

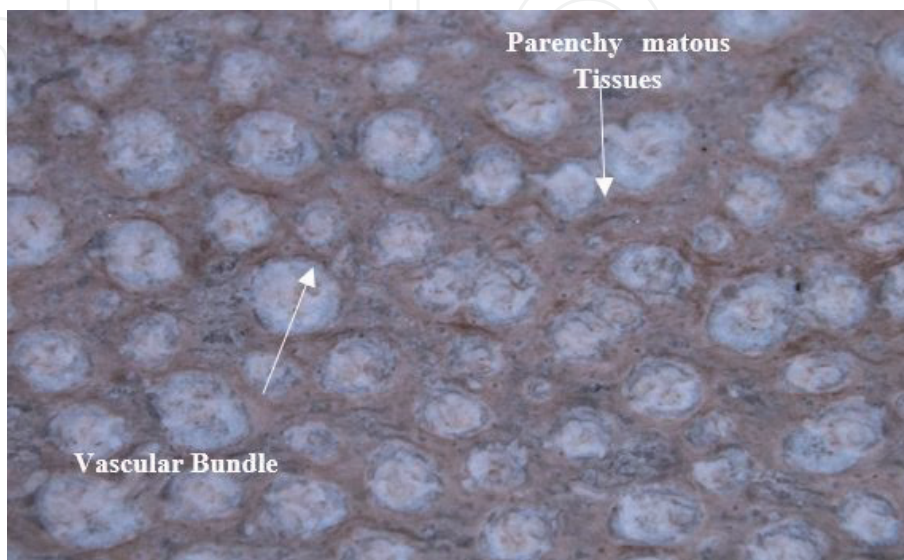


Figure 5.
High-performance micrograph of inner part on oil palm fronds at transverse sectional view (2 × magnification).

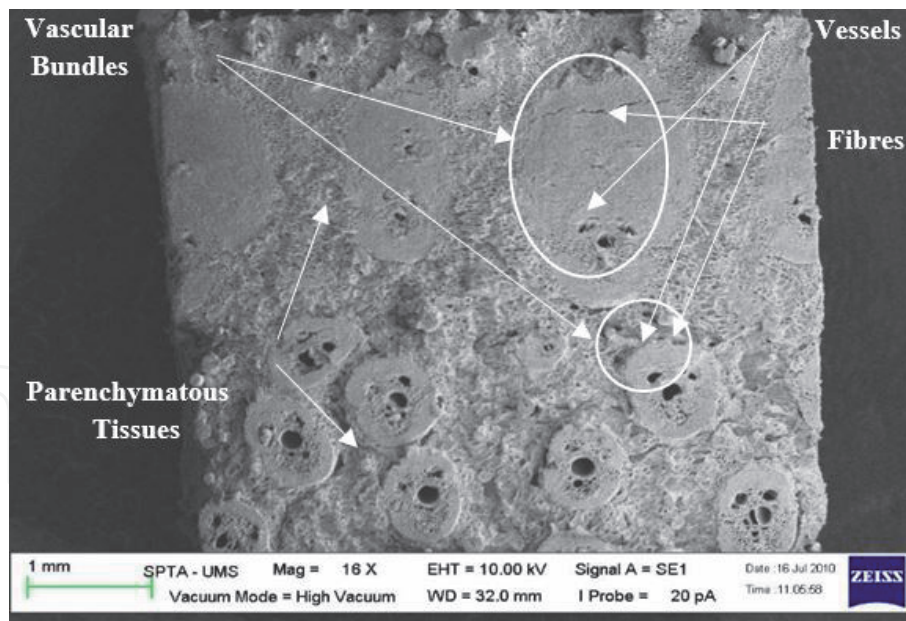


Figure 6.
SEM of oil palm fronds at the transverse sectional view (16× magnification).

vascular bundles over the transverse section, most of the vascular bundles were oriented randomly. **Figure 6** clearly shows the difference in sizes and population of vascular bundles towards the outer to the central part of the oil palm fronds using scanning electron microscopy (SEM).

3.1.1 Vascular bundles

Vascular bundles serve as the supporting structure and the transport system of the oil palm fronds. Typically, the vascular bundles are composed of fibre, vessel or metaxylem, protoxylem, protophloem or sieve tubes, axial parenchyma, stigmata, and companion cells [30, 32]. Most of the vascular bundles are composed of one or two-vessel cells. Though uncommon, vascular bundles with more numerous than three vessels designed tangentially or in batches can also be observed scattered, especially in the core section. Widespread protoxylem lessened vascular tissue, and little bundles with tiny fibrous tissues are also regularly seen scattered between the broader bundles in the core section. The arrangement of fibrous strands depends on the amount of bundles present [33]. Phloem can be found located between the vessel and fibre sheath. Protoxylems are present at the outer part adjacent to the vessel. The number of vascular bundles for the frond is the same and permanent. The growth is happening on vascular bundles diameter only and not its quantity [34].

Based on the visual investigation under SEM, the vascular bundle consists of one or two large vessels and surrounded by fibres cells (**Figure 7**). These vascular bundles are embedded around parenchymatous tissue. The vascular bundles are surrounded by parenchymatous ground tissue. Therefore the wood material from this species is not comparable to the woods produced from both dicotyledons and gymnosperms species which developed from the secondary xylem [35]. The fibres that compose the vascular bundles are arranged in a crescent-shaped sheath surrounding the phloem. The fibres are irregular in length and wall thickness. The number of fibres associated with vascular bundles and the number of secondary walls deposited in them on the location of the bundles within fronds [36].

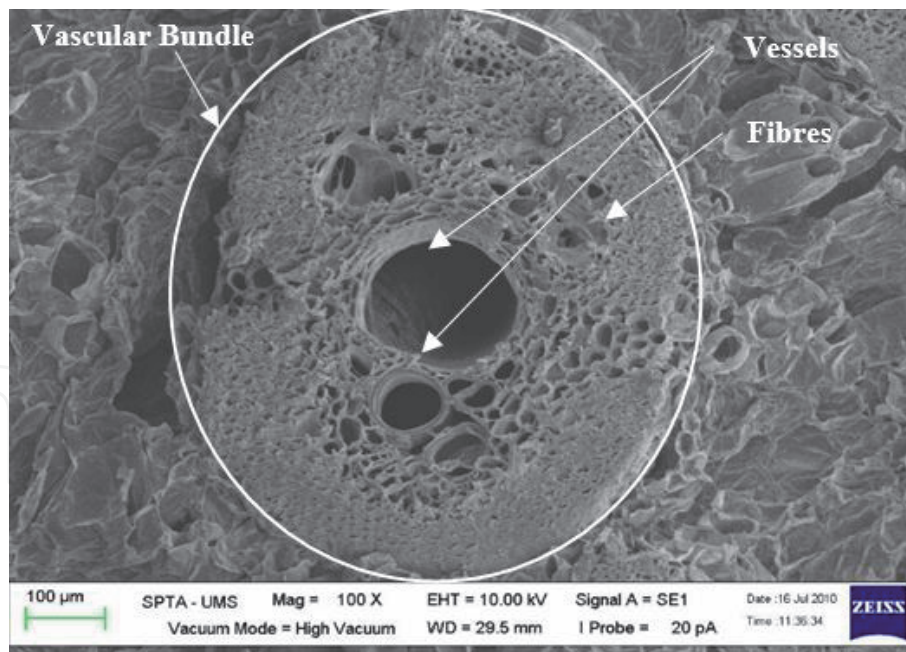


Figure 7.
SEM of vascular bundle in oil palm fronds at the transverse sectional view ($100\times$ magnification).

3.1.2 Vessel structure

According to the vascular bundle structure presented in **Figure 7**, the presence of large vessels varies from one to three vessels. The term of large vessel here is the tracheary elements of a vascular bundle like the oil palm trunk [35]. The extensive surveys of tracheary elements in palms are conducted by Tomlinson [30], and Bierhorst and Zamora [37], and these studies can be applied to oil palm fronds. Further, Parthasarathy and Klotz [28] found the palm vascular bundle clusters tracheary elements display a gradation in morphology from protoxylem within beginning to final metaxylem. The end walls of the tracheary part manifest a rising degree of evolutionary specialization, i.e., they enhance decreasingly tracheid-like. The protoxylem tracheary parts and any of the narrow early metaxylem elements approximately evermore appear to be tracheids. The remaining thin metaxylem elements and the broad late metaxylem elements present varying degrees of specialization, depending on the organ and the species.

Large vessels with very thick vessel-wall were predicted as the main component responsible for transporting the nutrient. This statement was in agreement with the result from Lim and Khoo [33] that has been studied on the oil palm trunk. **Figures 8** and **9** show the vessel on a close view in the vascular bundle from two different sectional views at transverse sectional and at the longitudinal views.

3.1.3 Fibre structure

The oil palm fronds consist of primary vascular bundles embedded in parenchyma ground tissues. Oil palm fronds fibres spread beyond the vascular bundles and loaded by the parenchyma cells. Fibres have a tight end, mainly influenced. The composition of fibres was essentially comparable to common woods, including softwood and hardwood, which comprise pits, cell walls, and lumen. Fibres in the oil palm fronds played a vital role in the strengthening mechanism of the composite when stress was transferred between the matrix and fibres. The SEM of fibres contains in vascular bundles is displayed in **Figures 10** and **11**.

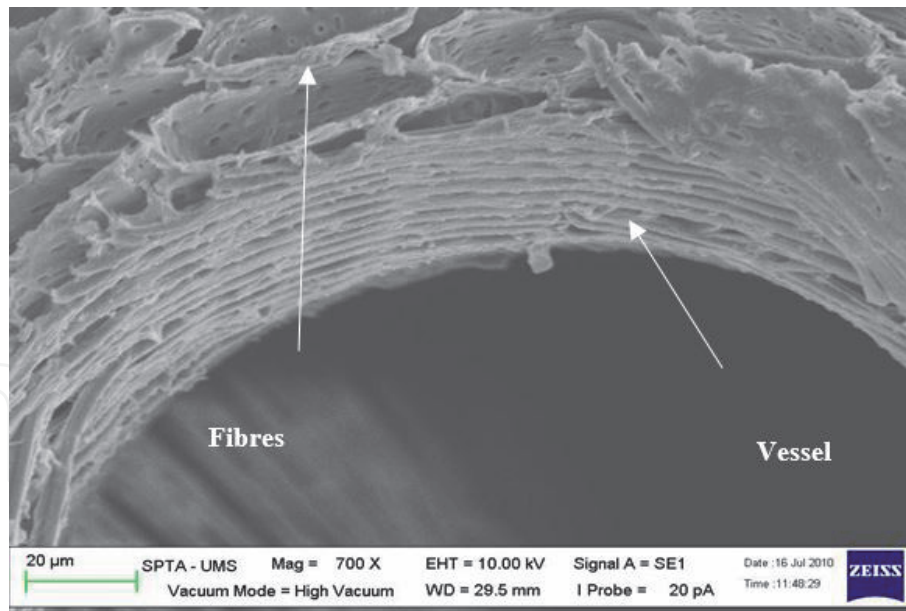


Figure 8.
SEM of the vessel in oil palm fronds at the transverse sectional view (700× magnification).

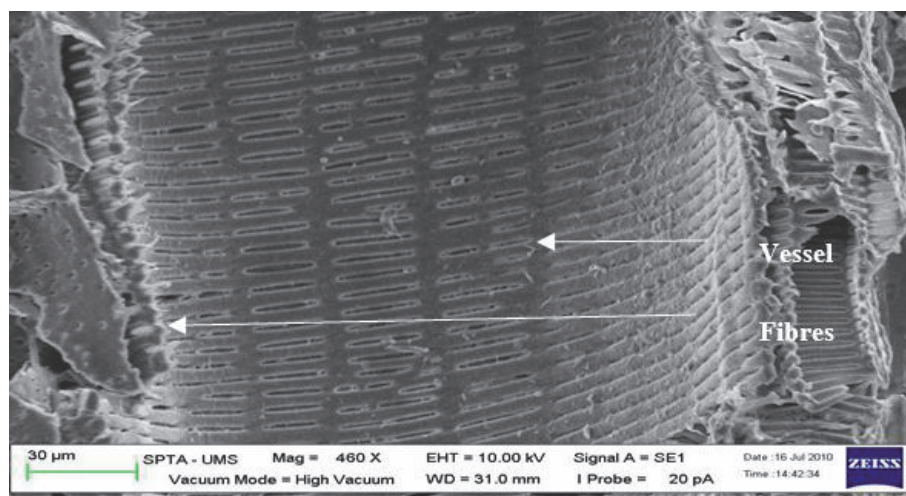


Figure 9.
SEM of the vessel in oil palm fronds at the longitudinal sectional view (460× magnification).

The transverse sectional view of oil palm fronds in **Figure 10** shows that the fibres attached to the others in very compact formations like fibres in oil palm trunk. **Figure 11** presented the structure of the fibre in oil palm fronds closely. Various sizes and shapes were distinguished, e.g. spherical, triangular, and rectangular. The presence of pits also identified at the fibre wall and companion cells, like shown in **Figure 11**. The walls might be thick or thin, and the small or large lumina. The primary function of fibres was predicted to provide strength support to the living oil palm fronds.

3.1.4 Parenchymatous tissues

Parenchymatous tissues are not only found in the trunk but also found abundantly in the fronds. They are food storage elements and must, therefore, remain alive for an extended period. Similar to vascular bundle shapes, parenchyma tissues show two different forms, which are isodiametric-shape and elongated-shape. The isodiametric cells have thin walls, while the elongated cells have thicker poly-

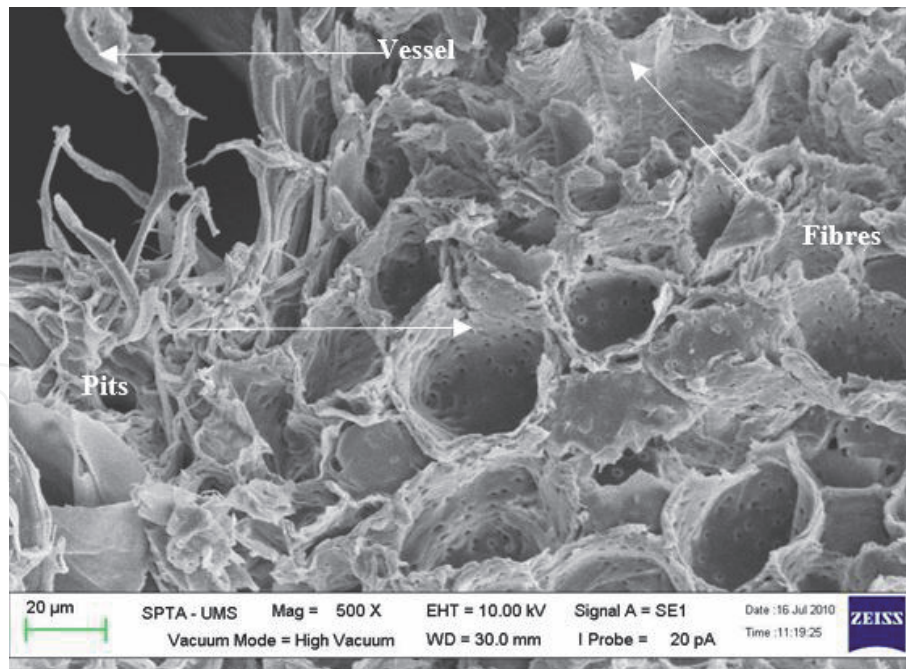


Figure 10.
SEM of fibres in oil palm fronds at the transverse sectional view (500 × magnification).

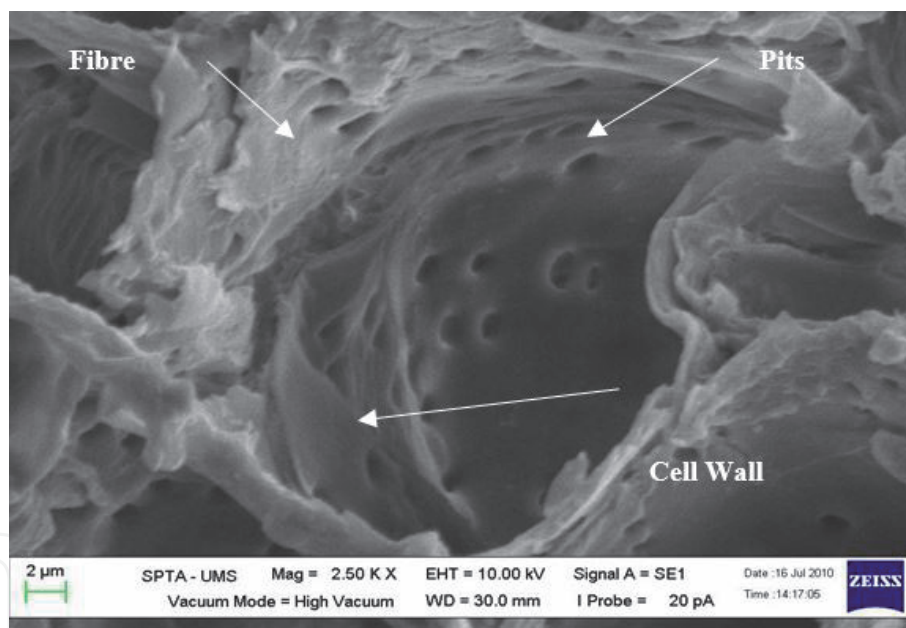


Figure 11.
SEM of fibres in oil palm fronds at the transverse sectional view (2500 × magnification).

laminate walls [38]. Parenchyma tissues are also found associated with the vascular bundles in the axial position, an elongated shape. They are found at the inner tip of the vascular bundles related to the vessels, protophloem, and protoxylems. They may have a special function in water transport, like the vessel-associated cells in the dicotyledonous trees [33]. These parenchymatous tissues consist mainly of ground parenchyma, parenchyma strands, sieve elements, and companion cells [36].

The parenchymatous ground cells consist mainly of thin-walled spherical cells, except in the vascular bundles. The walls are progressively thicker and darker from the inner to the outer region. Parenchyma tissues contain much sugar and starch as food storage elements, which are soluble in water and NaOH [39]. Parenchyma cells of oil palm fronds functioned as the ground tissues that make up the bulk of oil palm

fronds structures and are used as storage for food. Parenchyma cells of oil palm fronds were mainly in the form of spherical cells with thin-walled and brick-like formations, but in the narrow space or area between vascular bundles, they were familiar as elongated cells and oval-cells, and this is similar to oil palm trunk. Physically, this tissue was spongy and moist in green condition and very lightweight and easy to separate one cell from the others. Parenchyma cells also contain some amount of chemical composition [40]. **Figure 12** shows detail of the structure of parenchyma cells under SEM.

Figure 12 shows that many pits were observed on the primary cell wall, which functioned for water or nutrient transport purposes. Based on this fact, it is logically accepted why ground parenchymatous tissue was very hygroscopic. It was easy to evaporate when the temperature is rising and also easy to absorb the moisture in high humidity conditions. A study by Tomimura [41] and Sun et al. [42] found that parenchyma contained a high amount of starch and lignin compared to vascular bundles. Besides, parenchyma ground tissue which cements the vascular bundles together is undesirable for the manufacture of wood-based products like pulp and composite boards. In pulp manufacture, these tissues consume chemicals and produce fines that may be lost during screening. The rounded parenchyma also reduces the paper strength properties. In particleboard manufacturing, it may interfere with the bonding between particles and will reduce strength properties.

3.2 Chemical composition of oil palm fronds

The chemical composition of biomass significantly varies due to their diverse origins and types. Biomass is generally composed of cellulose, hemicelluloses, lignin, and inert ash. Chemically, fronds strands are rich in holocelluloses (83.5%) and also high in α -cellulose (49.8%) [43]. The extractive oil palm oil fronds are about 4.5%, and the lignin content is about 20.5% [43]. This lignin content shows that it is lower than generally found in commonly hardwood, for eucalyptus of 22%. **Table 1** shows the chemical composition of oil palm fronds.

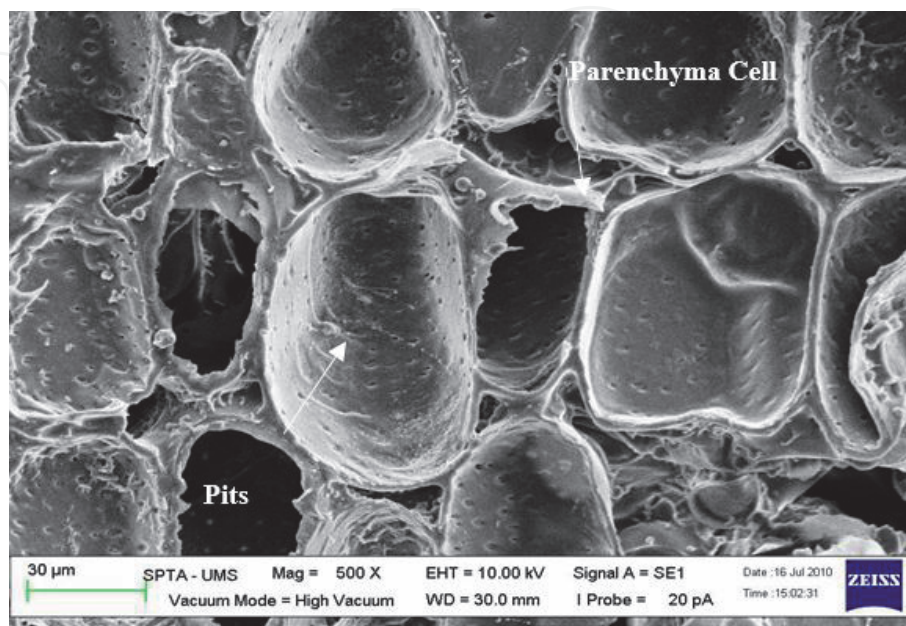


Figure 12. SEM of parenchyma cell in oil palm fronds at the transverse sectional view (500× magnification).

Composition	Chemical composition (%)				
	Extractive	Holocellulose	Cellulose	Lignin	Ash
Oil Palm Fronds	4.5	83.5	49.8	20.5	2.4

Source: Abdul Khalil et al. [43].

Table 1.
Chemical composition of oil palm fronds.

This is not surprising since oil palm trees are non-woody, and the requirement for structural support is lower compared to woody trees. The functional significance of lignin has long been associated with strength support for plant organs that enables increased growth in height [44, 45]. Its lacking will no longer allow plants to be upright [46]. It should also be noted that the fronds strands, like other non-wood fibres, contain comparatively high ash content. This characteristic might contribute to abnormal strength wear of processing equipment. The monomer composition of polysaccharides shows only glucose, xylose, and other monosaccharides representing less than 6%. Thus, it is in broad similarity with that of hardwoods [47, 48].

3.3 Physical properties of oil palm fronds

Physical properties of oil palm fronds are essential in contributing its characteristics as a raw material of producing a product that required the properties to stand against load. Many different wood properties have some influence on the processing of wood products. Since it is not possible to evaluate all these properties for all species concerned, it is necessary first to identify the essential characteristic to determine the quality of the products that are finally used [49]. The main physical properties are the moisture content, density as well as basic density.

3.3.1 Moisture content

The moisture content of oil palm fronds is similar to oil palm trunks. The oil palm moisture content recorded ranges between 100% and 500%. A progressive rise in moisture content is shown onward with the trunk height and towards the central section, while the lower and outer positions were should far lower values than the other two sections [33]. An increase in the number of vascular bundles causes a decrease in the percentage of parenchyma cells, which have a high capacity in water absorption [50].

3.3.2 Density

Due to its monocotyledonous nature, there is a tremendous variety of density values at different oil palm fronds like the oil palm trunk. The density values range for oil palm trunk is from 200 to 600 kg/m³ with an average density is 370 kg/m³. The density of the oil palm trunk decreases linearly with the trunk height and towards the centre of the trunk [33]. These fluctuations are due to various factors. Beyond the trunk, the density is mainly influenced by the number of vascular bundles per square unit, reducing the centre. Nonetheless, vascular bundles existing younger at the top end influenced changes in density onward trunk height. Although the bundle is smaller in size and cell walls are thinner, proportionally, a higher per square centimetre is higher.

3.4 Oil palm fronds strength properties

The oil palm trunk strength properties are proportional to the density variation recognized in both vertical and radial directions. The highest bending strength values from the peripheral lower portion, and the top portion of the central core highlighted the most insufficient strength. Variation of the compression strength parallel to grain also follows the same trend as the bending strength [51]. But, for the oil palm fronds, there is no strength testing done in raw material because compared to the oil palm trunk, there are no uses of oil palm fronds in raw material directly like the trunk.

Some studies have been done in manufacturing composite boards from oil palm fronds compared to their strength properties. Laemsak and Okuma [7] mentioned that there seems to be a good possibility for producing binderless boards using steam-exploded fibres of oil palm fronds considering the chemical components of oil palm fronds which are rich in hemicelluloses. The strength properties such as modulus of rupture (MOR) and modulus of elasticity (MOE) of the boards increased linearly with increasing board density as the standard hardboard. They reported that the boards made from fibres treated under a steam explosion condition of 25 N/cm² (steam pressure) and five minutes (digestion period) exhibited the maximum strength.

The compatibility of oil palm frond cement mixtures was tested in the hydration test, with magnesium chloride (MgCl₂) as an accelerator at different water and cement ratios [52]. He reported that the optimum weight ratio of cement-wood increased with decreasing wood powder size based on the equal specific surface area ratio of cement/wood in the hydration test and board manufacturing. The addition of magnesium chloride improved the compatibility of oil palm fronds with cement, enhancing the cement hydration and ultimate board strength properties. The study dealt with the effects of a curing method that uses gaseous and supercritical CO₂ to see its impact on the properties of oil palm fronds cement-bonded board manufactured by the conventional cold-press setting method were carried out by Hermawan et al. [53]. The study showed that high-performance cement-bonded boards made from oil palm fronds were successfully manufactured using the CO₂ curing method.

4. Processing of compressed oil palm fronds

The oil palm fronds were obtained from the plantation and selected based on decay-free and no defect. The oil palm fronds were taken from the plantation were divided into three groups according to their maturity. They were the old maturity fronds that have been taken from the below of the fronds crown. The intermediate maturity fronds were obtained from the middle of the frond's crown. The third group was the young maturity fronds that have been taken from the above of the frond's crown. The difference between maturity groups is shown in **Figure 13**.

4.1 Compressed oil palm fronds preparation

Figure 14 shows the fresh fronds was obtained from the oil palm tree. Leaflets were removed from the fronds, and then each maturity group was divided into three portions: the bottom, middle and top portion shown in **Figure 15**. A disc about 10 cm in the middle was cut from every portion for the physical properties study for the raw of oil palm fronds, and the rest were peeled of their skin and sliced in the longitudinal direction as shown in **Figure 16**. These sliced fronds were then compressed using rollers compressed machine to increase their density before undergoing sun-drying which has been shown in **Figure 17**.



Figure 13.
Differences between maturities of oil palm fronds.



Figure 14.
Fresh oil palm fronds obtain from the oil palm tree.

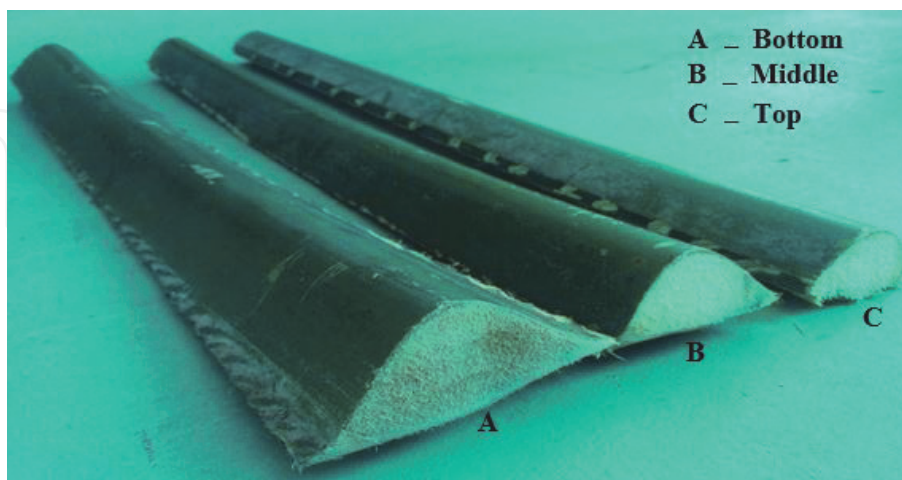


Figure 15.
Portion division from the oil palm fronds.

4.2 Air drying process

All the compressed oil palm fronds then have been dried in sun-drying for 12 hours until almost the moisture is removed from the fibre and their moisture

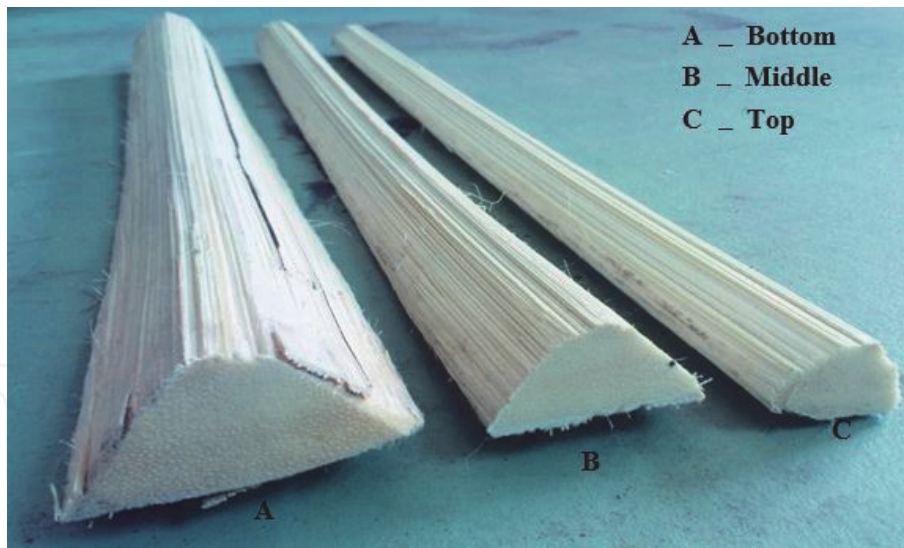


Figure 16.
The skin peeled off oil palm fronds.

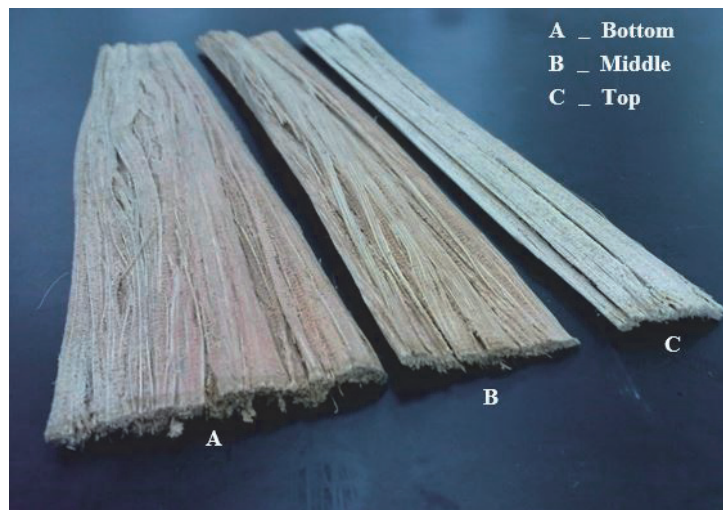


Figure 17.
The compressed oil palm fronds.



Figure 18.
Compressed oil palm fronds under sun-drying.

content was about 12% measured by MC meter as shown in **Figure 18**. This air-drying mainly enhance their durability against fungi and insect attacks.

5. Manufacturing of composite board from oil palm fronds

The oil palm frond composite boards used in this study were made on a laboratory scale but follow the ISO standard. The oil palm fronds had been processed as compressed oil palm fronds to form such a potential composite board in this topic. The leaflets and epidermis are first manually removed from the fronds by a scraper. They were then sliced longitudinally into thin layers and compressed into 2-3 mm in thickness. The material was then air-dried under the shed before added with 12-15% of phenol and urea-formaldehyde resins and hot-pressed into composite boards.



Figure 19.
Layers of palm oil fronds being compressed using a hotpress machine.



Figure 20.
Composite board from compressed oil palm fronds were trimmed.

Hardner NH_4Cl at 1% later added forming layers which were compressed into 350 mm (length) \times 350 mm (width) \times 20 mm (thickness) boards. This was done by transferring the material to a single-opening hydraulic hot-pressed machine with a platen temperature of $125\pm 5^\circ\text{C}$ for phenol-formaldehyde resin and $100\pm 5^\circ\text{C}$ for urea-formaldehyde resin and pressed into the desired shape for subsequent testing.

The composite board from compressed oil palm fronds was pressed using a three-step-down method of pressing among 40 secs/mm for phenol-formaldehyde resin, meanwhile 30 secs/mm for urea-formaldehyde resin. Thickness spacing bars of 20 mm thick were inserted between the hot platens during hot pressing to ensure the desired board thickness is shown in **Figure 19**. All these composite boards were trimmed as shown in **Figure 20** and cut into various size test specimens and then conditioned at $20\pm 3^\circ\text{C}$ and $65\pm 3\%$ relative humidity (RH) for 72 hours prior for testing to produce equilibrium moisture content of about $12\pm 1\%$. More samples of the composite board from compressed oil palm fronds were shown in **Figures 21–24**.

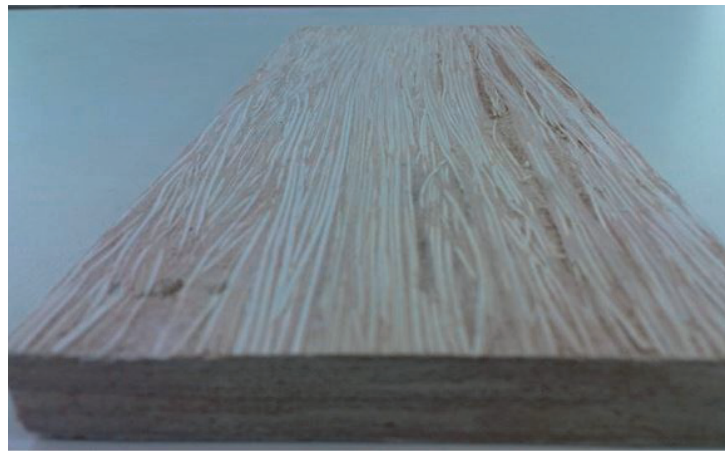


Figure 21.
Front view of the compressed oil palm fronds board.

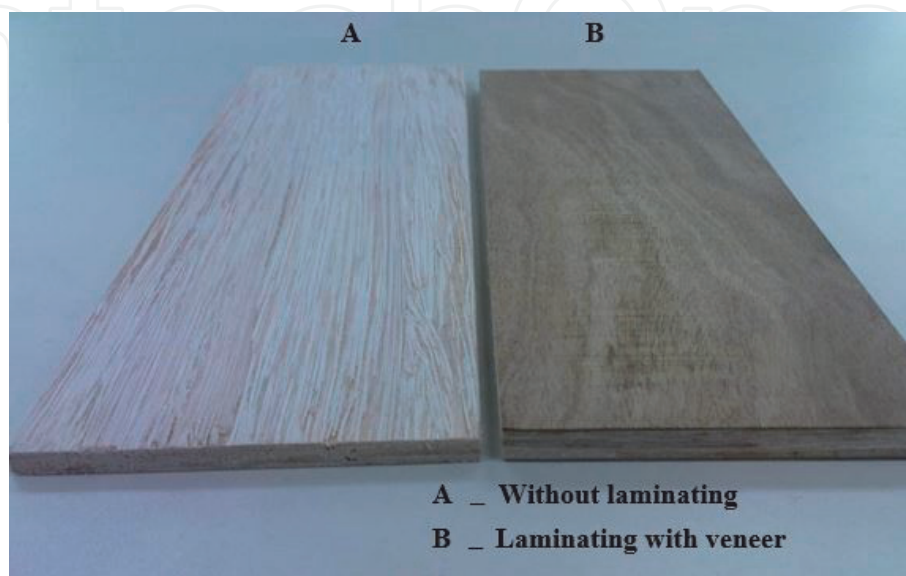


Figure 22.
The compressed oil palm fronds boards can be laminating with veneers.



Figure 23.
The compressed oil palm fronds boards at differences thickness.



Figure 24.
High-performance micrograph of the phenol-formaldehyde composite board from compressed oil palm fronds at the longitudinal sectional view (2× magnification).

6. Physical properties of composite board from compressed oil palm fronds

To understand the composite board behaviours and performances, it is necessary to consider first some of the basic physical properties which are affecting its strength properties furthermore. Several physical properties of the composite board from compressed oil palm fronds were investigated, which are density and basic density-based based on its maturity groups, portions, and resin types of the composite board that had been produced.

6.1 Density of composite board from compressed oil palm fronds

Density is an excellent indicator of the amount of substance in a piece of wood [40]. The density of the composite board from compressed oil palm fronds will depend on the maturity groups, portions, and types of the resin that have been used for bonding this composite board. **Table 2** shows the mean value results for the density of the composite board for each maturity group, portion, and resin type. **Table 2**, showed that the highest density for this composite board came was from

Maturity Groups	Density (g/cm ³) at different Portions		
	Bottom	Middle	Top
Matured			
Phenol Formaldehyde Composite Board	0.45	0.44	0.42
Urea Formaldehyde Composite Board	0.46	0.43	0.42
Intermediate			
Phenol Formaldehyde Composite Board	0.43	0.42	0.40
Urea Formaldehyde Composite Board	0.44	0.42	0.41
Young			
Phenol Formaldehyde Composite Board	0.42	0.41	0.40
Urea Formaldehyde Composite Board	0.42	0.41	0.40

Source: Rasat et al. [54].

Table 2.
Value for density of the composite board.

the bottom portion for each maturity group followed by the middle and then top portions. The matured maturity group possessed the highest density values for every portion of the intermediate and young maturity groups.

According to the obtained results in **Table 2**, the decreased summarised composite board from compressed oil palm fronds density from the bottom to top portions for each maturity group and from the old to young maturity groups for each portion was influenced by internal structure in the oil palm fronds by its abundance of vascular bundles and parenchymatous tissues. The analysis of variance (ANOVA) in **Table 7** indicates the significant difference between density with maturity groups and portions. Nevertheless, no significant difference was indicated between the utilization of resin to produce composite boards. Hence, the density value of the composite board did not affect the types of resin.

Nonetheless, the compactness of the compressed oil palm fronds higher than the raw oil palm fronds density by the effect of resin penetration used in producing this composite board. It was found that the presence of both resins could increase the density of the composite board from compressed oil palm fronds that cause the increase in a material substance per unit volume in this composite board.

6.2 Basic density of composite board from compressed oil palm fronds

Table 3 indicates the mean values of basic density for the composite panel from compressed oil palm fronds for each maturity group, portion, and resin types. Decreases in values of the basic density from the bottom to the top portion for each maturity group and from the old to young maturity groups for each portion were caused by the high concentration of fibrous vascular bundles of the oil palm composite boards [55, 56]. The basic density differs according to their cell size, cell wall thickness, and relative amount of solid cell wall material. Mature and thickly cells occurred at the bottom part of the wood resulting in higher basic density values than other parts. The decreases in the basic density value from the fronds' bottom portion to the top is due to the growing differences in the anatomical cell maturity development [57]. Both density and basic density are the main factors affecting the strength properties of wood.

The analysis of variance (ANOVA) in **Table 7** indicates the significant difference between density with maturity groups and portions. Nevertheless, no significant

Maturity Groups	Basic Density (g/cm ³) at different Portions		
	Bottom	Middle	Top
Matured			
Phenol Formaldehyde Composite Board	0.38	0.36	0.33
Urea Formaldehyde Composite Board	0.39	0.35	0.32
Intermediate			
Phenol Formaldehyde Composite Board	0.36	0.35	0.32
Urea Formaldehyde Composite Board	0.37	0.34	0.31
Young			
Phenol Formaldehyde Composite Board	0.34	0.33	0.30
Urea Formaldehyde Composite Board	0.34	0.32	0.30

Source: Rasat et al. [54].

Table 3.
 The basic density of the composite board.

difference was indicated between the utilization of resin to produce composite boards. Hence, the density value of the composite boards did not affect the types of resin. According to Paridah and Anis [58], the parenchyma acts similar to a sponge and easily absorbed moisture. On that account, this composite could effortlessly absorb phenol and urea-formaldehyde resin during the production process and increasing the basic density of the composite board of compressed oil palm fronds.

7. Strength properties of composite board from compressed oil palm fronds

The strength characteristics of wood are stratagems of its resistance to exterior forces, which direct deform its mass [35]. Such forces depend on their measurement and loading method (bending, compression, shear, tension, etc.). Tsoumis [59] declared that wood manifests various strength properties in different growth paths; therefore, it is strongly anisotropic. According to Bowyer et al. [60], In structural applications, strength properties are usually the most important aspects to define the products used. There are appointed as one of the primary criteria for selecting the material. Strength of wood structural practiced for wall sheathing, floor joint and rafters, and also subflooring application. [35].

Several strength properties were tested in this study, including static bending strength (modulus of elasticity (MOE) and modulus of rupture (MOR)) and compression strength. The testing was carried out based on International Organization for Standardization (ISO) standard for the strength properties evaluation. The analysis of strength properties of the composite board from compressed oil palm fronds has specifically looked into the effect of types of resin, maturity groups, and portions. Phenol and urea-formaldehyde were the resins used in producing this composite board.

7.1 Static bending strength of composite board from compressed oil palm fronds

According to Erwinsyah [35], the static bending strength refers to the tests performed. Bending stress is applied to the specimen to determine the stiffness or

MOE of the samples and the amount of force required to cause the sample to fail expressed as the MOR. Erwinsyah also postulated that the bending strength of wood is commonly expressed in MOR and is the most vital parameters that is occasionally used for engineering purposes [61].

The summary result in the static bending, which included the MOE and MOR strength, can be referred to **Tables 4** and **5**. Composite boards made from the bottom portion of the fronds possess the highest value for MOE and MOR strengths. The intermediate and young maturity groups follow this. The strength values of the boards both from phenol and urea-formaldehyde resin decreases from the bottom to top portions for every maturity group and from the old to young maturity groups for each portion, respectively. The MOE values of the maturity group from the bottom, middle, and top portions for the phenol-formaldehyde composite board were at 999.61, 952.29, and 844.18 N/mm², respectively. The MOE for the urea-formaldehyde composite board at 980.31, 949.40, and 840.40 N/mm². The MOE

Maturity Groups	Static Bending MOE (N/mm ²) of Portions		
	Bottom	Middle	Top
Matured			
Phenol-Formaldehyde Composite Board	999.61	952.29	844.18
Urea-Formaldehyde Composite Board	980.31	949.40	840.40
Intermediate			
Phenol-Formaldehyde Composite Board	979.15	942.44	817.29
Urea-Formaldehyde Composite Board	953.93	928.34	776.04
Young			
Phenol-Formaldehyde Composite Board	935.36	837.24	761.14
Urea-Formaldehyde Composite Board	936.24	836.67	666.30

Table 4.
MOE static bending strength of the composite board.

Maturity Groups	Static Bending MOR (N/mm ²) of Portions		
	Bottom	Middle	Top
Matured			
Phenol-Formaldehyde Composite Board	16.66	12.55	11.72
Urea-Formaldehyde Composite Board	15.40	12.38	11.63
Intermediate			
Phenol-Formaldehyde Composite Board	14.38	12.37	10.87
Urea-Formaldehyde Composite Board	12.62	12.07	10.51
Young			
Phenol-Formaldehyde Composite Board	12.61	11.62	10.27
Urea-Formaldehyde Composite Board	12.25	11.19	9.10

Source: Rasat et al. [54].

Table 5.
Mean value for MOR static bending strength of the composite board.

strength decreases from bottom to top portion for the maturity group either for phenol or urea-formaldehyde composite board, and the same situation was done for the other two maturity groups, the intermediate and young maturity groups.

Based on the results obtained from the study of the effect of resin types in static bending, it was found that the composite board from phenol-formaldehyde resin possessed a high value of both MOE and MOR test than urea-formaldehyde resin. The latter contained a high amount of solid content compared to phenol-formaldehyde resin.

The MOE strength of boards made from the bottom portion from the matured, intermediate, and young maturity groups of the phenol-formaldehyde composite board was 999.61, 979.15, and 935.36 N/mm², respectively. The MOE strength of the urea-formaldehyde composite board was at 980.31, 953.93, and 936.24 N/mm² from the matured, intermediate, and young maturity groups. The MOE strength decreases from the matured to young maturity groups for the bottom portion for both resin types of the composite boards. The MOE strength when the specimen reached the breaking point and then could not recover its shape, where the load achieves its maximum value, is called MOR. This strength property is one of the significant parameters which usually used for engineering purposes. Relating to the resulting test of MOR of the composite board from compressed oil palm fronds at the different maturity groups, portions, and resin types, the summarised data of mean values is presented in **Table 5**.

The MOR of the compressed oil palm fronds composite boards increases in strength from the top to the bottom portions for the maturity group and from young to matured fronds for every portion. The MOR strength for the maturity group was at 16.66, 12.55, and 11.72 N/mm², respectively for the top, middle, and bottom portions for phenol-formaldehyde resin, while the MOR for the urea-formaldehyde were at 11.63, 12.38, and 15.40 N/mm². Similar trends were observed in the intermediate and young maturity groups from the bottom towards the top portions. The results in **Table 5** showed that the bottom portion for each maturity group (matures, intermediate, and young) and the portions grouping from the phenol-formaldehyde composite boards were at 16.66, 14.38, and 12.16 N/mm² and, the MOR for urea-formaldehyde composite boards at 15.40, 12.62 and 12.25 N/mm² respectively. The strengths decrease from the matured towards the bottom portion for both resin types used in the maturity groups. Similar trends were noted in the MOE values. The MOR decreases from bottom to top portions for each maturity group and from old towards young maturity groups for every portion.

The values of both the MOE and MOR for the oil palm frond compressed composite boards increases from the top to the bottom portions. Similar observations were noted in the frond maturity groups from young, intermediate, and matured groups. These occurred to both of the composite boards made from phenol and urea-formaldehyde resin. The decreases can explain the trend of variations in the MOE and MOR values and the tree height in the maturity of wood and fibre length from top to the bottom of the tree [62]. This is logically accepted due to vascular bundles that decrease from the bottom to top portions along with the oil palm fronds and the old to young maturity groups. A large amount of the vascular bundle in the oil palm fronds containing a higher quantity of fibre cells gives higher density and basic density values in both the composites. According to Haygreen and Bowyer [57], the woody materials with higher values density and basic density will directly possess higher strength. The bottom portion has a higher value for both MOE and MOR strengths compared to the middle and top portions for the maturity group in every portion [57]. Based on the results obtained from the study of the effect of resin types in static bending, it was found that the composite panel from phenol-formaldehyde resin possessed a high value of both MOE and MOR test than

urea-formaldehyde resin. By the latter contained a high amount of solid content compared to phenol-formaldehyde resin [63].

The static bending was significantly affected by the density and basic density value [63]. This thus gives effect to the MOE and MOR strengths of the composite boards from top to bottom portions. The ANOVA in **Table 7** supports this statement. The result also showed that the composite boards from phenol-formaldehyde resin possessed a higher value of both MOE and MOR test than urea urea-formaldehyde resin, which contained a higher amount of solid content compared to phenol-formaldehyde resin.

Furthermore, the distribution of phenol-formaldehyde resin is located irregularly in the composite boards' structures [40]. When the stress was applied, the stress could not be transferred consistently between the fibre and matrix. Besides, the penetration of high viscosity of urea-formaldehyde resin probably breaks the cell wall of the composite board from compressed oil palm fronds [40].

7.2 Compression strength of composite board from compressed oil palm fronds

Compression strength is defined as the maximum stress sustained by compression of a specimen with the specimen having a ratio of length to smallest dimension [64]. In contrast, Ronald and Gjinoli [65] reported that the characteristic of the compression load-deformation curve was similar to those for static bending strength. The compression strength of the composite is strongly dependent on the effectiveness of the matrix in supporting the fibre against buckling [66].

The obtained data was examined using statistical analysis to define the effect of three parameters like static bending strength test, which were based on maturity groups, portions including types of resin to the compression strength of the composite board from compressed oil palm fronds. According to the testing result, the data is presented in **Table 6** which was based on mean value compression strength. From the display result in **Table 6**, the compression strength value of the old maturity group from bottom to top portions was 473.17, 395.93, and 260.22 N/mm² for the phenol-formaldehyde composite board, while for the urea-formaldehyde composite board, the result was 459.52, 344.60, and 260.00 N/mm² respectively. It can be observed that the compression strength was decreased from the bottom

Maturity Groups	Compression (N/mm ²) of Portions		
	Bottom	Middle	Top
Matured			
Phenol Formaldehyde Composite Board	473.17	395.93	260.22
Urea Formaldehyde Composite Board	459.52	344.60	260.00
Intermediate			
Phenol Formaldehyde Composite Board	453.67	318.88	196.71
Urea Formaldehyde Composite Board	431.88	274.90	190.70
Young			
Phenol Formaldehyde Composite Board	301.46	235.60	183.48
Urea Formaldehyde Composite Board	312.94	198.79	181.06

Source: Rasat et al. [54].

Table 6.
The value for compression strength of the composite board.

portion towards to middle and top portions for the old maturity group. Similar decrement distribution data have been done for intermediate and young maturity groups towards the bottom, middle, and top portions.

Table 6 showed that the trend for each oil palm fronds composite made from matured, intermediate, and young in maturity groups. The result at matured, intermediate, and young maturity groups was at 473.17, 453.67, and 301.46 N/mm² for the phenol-formaldehyde composite boards. The result for the urea-formaldehyde composite was at 459.52, 431.88, and 312.94 N/mm², respectively. It clearly shows the decrement from mature to intermediate and young groups for the bottom portion. The same trends were also observed in the others two portions (the middle and top).

This was due to the differences in vascular bundle abundance and oil palm fronds, affecting the value of density and basic density. The differences between the latter promote the distribution result of compression strength for the maturity groups and portions. The bottom portion scored higher results in compression strength as compared to others portions. **Table 7** tabulated the ANOVA results that indicate the significant difference between compression strength with maturity groups and portions. According to Oyagade AND Fasulu [67] and Nordahlia [68], some wood properties, including compression strength failure, typically occur in the low density of the wood.

The results obtained showed that the phenol-formaldehyde composite boards possessed higher values than the strength of the urea-formaldehyde composite. This can be attributed to the fact that properly cured phenol-formaldehyde composite resin is usually tougher than the bonded [69]. However, the differences in the compression strengths are not significant as shown in **Table 7**. Therefore, we can conclude that either resin's use does not matter as long as it is economically feasible to produce the mass quantity of the oil palm frond composite boards.

Source of Variance	Dependent Variable	Sum of Square	df	Mean Square	F-Ratio
Maturity	Density	0.01	2	0.01	7.94**
	Basic Density	0.01	2	0.02	28.75**
	MOE Bending	155675.00	2	77837.50	57.05**
	MOR Bending	79.02	2	39.51	40.39**
	Compression	255794.00	2	127897.00	63.81**
Portion	Density	0.01	2	0.01	8.26**
	Basic Density	0.04	2	0.01	28.75**
	MOE Bending	507856.00	2	253928.00	186.12**
	MOR Bending	157.72	2	78.86	80.62**
	Compression	565023.00	2	282512.00	140.95**
Resin type	Density	0.00	1	0.00	0.20 ^{ns}
	Basic Density	0.00	1	0.00	1.28 ^{ns}
	MOE Bending	11232.80	1	11232.80	8.23 ^{ns}
	MOR Bending	8.23	1	8.23	8.41 ^{ns}
	Compression	7538.01	1	7538.01	3.76 ^{ns}

Source: Rasat et al. [54].

**i indicates citation of the researcher who conducted and produced the data/results.

Table 7.
 ANOVA on physical and strength properties of composite board.

8. ANOVA on physical and strength properties of composite board oil palm fronds

The analysis of variance (ANOVA) on the physical and the strength properties of the composite oil palm fronds is shown in **Table 7**. The ANOVA was used to determine the significant level between the physical and the strength properties with the dependent variables such as the maturity groups, portions, and types of resin used in the boards made. Based on the ANOVA (**Table 7**), there were significant differences between the physical and strength properties of the boards. Significant differences exist between the maturity groups and the portions. It shows that the physical and strength properties of the boards were affected and influenced by these factors—substantial differences at $p\text{-value} \leq 0.01$ exists between them. No significant difference exists between physical properties and strength properties with the application in the types of resin used. The phenol or urea-formaldehyde resin used to produce these boards give quite similar values in the test results.

9. Microstructural of composite board from compressed oil palm fronds

The microstructural observation of the composite board from compressed oil palm fronds was carried out with the help of high-performance microscopy, and a more detailed structure has been observed by scanning electron microscopy (SEM). More attention has been done to the microscopic resin penetration of the composite board from compressed oil palm fronds. The macroscopic structural characteristics of the composite board are the features that are using high-performance microscopy to magnify from 0.75 to 8.0 times. **Figures 24** and **25** show the roughly structural composite board from compressed oil palm fronds at the longitudinal sectional view for phenol and urea-formaldehyde composite board that had been observed under high-performance microscopy.

Figure 24 showed that the reddish colour of the composite board had been affected by phenol-formaldehyde resin colour naturally, and the same goes for the urea-formaldehyde composite board that shown whitish in the colour of its



Figure 25. High-performance micrograph of the urea-formaldehyde composite board from compressed oil palm fronds at the longitudinal sectional view ($2\times$ magnification).

appearances according to **Figure 25**. Appearances comparison among both of them resulted in the composite board from urea-formaldehyde resin, which gave better appearance quality than the composite board from phenol-formaldehyde resin, which is one reason why urea-formaldehyde resin has been used for internal usage of mostly wood-based composites. This composite board is formed layer by layer like laminated veneer lumber (LVL) because of its parallel arrangement among the compressed oil palm fronds. A more complex arrangement of this composite board has been presented in **Figures 26** and **27** under SEM observation at different magnification levels.

9.1 Resin penetration on composite board from compressed oil palm fronds

The high porous morphology of compressed oil palm fronds helps the resin be located and filled within the space, improving the characteristics of the composite board from compressed oil palm fronds. According to the obtained results, the density of the composite board was generally increased than oil palm fronds, and it

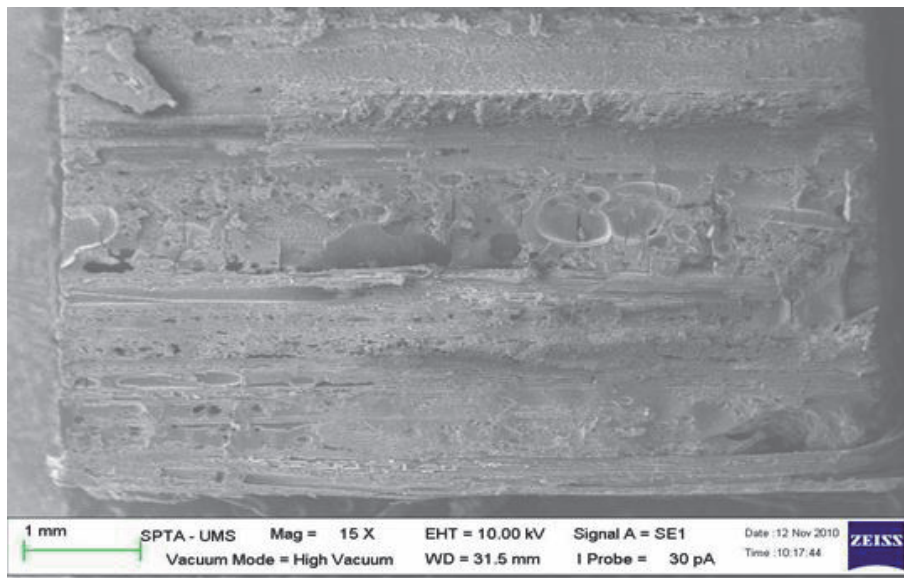


Figure 26.
SEM of the composite board from compressed oil palm fronds at longitudinal sectional view (15× magnification).

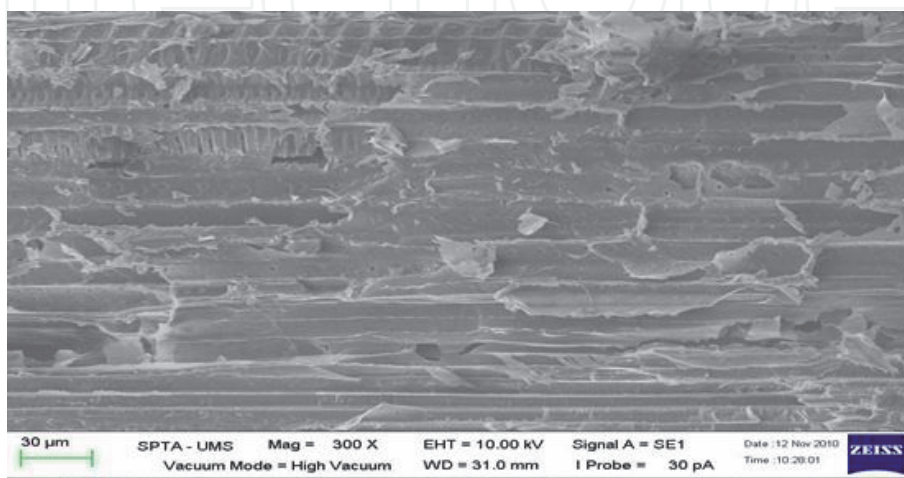


Figure 27.
SEM of the composite board from compressed oil palm fronds at longitudinal sectional view (300× magnification).

can be observed that an increase of resin penetration increased wood density and basic density result. This is because the resin reinforcement was applied to improve the wood features of the composite board and logically accepted the fact that the resin penetrated through the intercellular cavities of the composite board from compressed oil palm fronds, as shown in **Figure 28**.

The microscopic image of resin penetration on the composite boards from compressed oil palm fronds is presented in detail are shown in **Figures 29** and **30**. The strength increases with the enhancement in the density and basic density of the composite board. Most of the tested specimens increase their strength properties, including MOE of static bending strength and MOR of static bending and compression strength that have been tested in this study. It is attributed that the applied resin to the compressed oil palm fronds to form them into composite board was affecting positively to improve the strength properties of the composite board from compressed oil palm fronds. However, the different types of resin used in

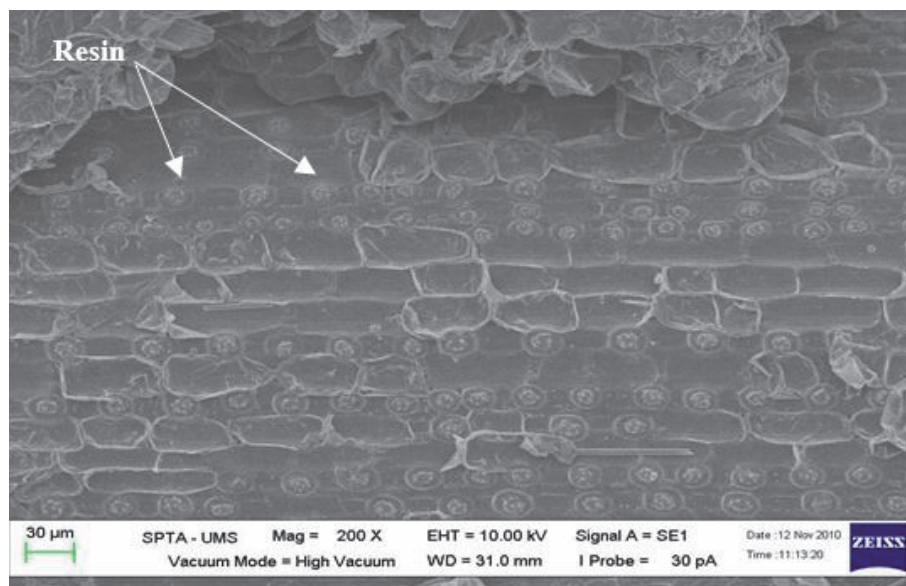


Figure 28.
SEM of resin penetration on composite board from compressed oil palm fronds (200× magnification).

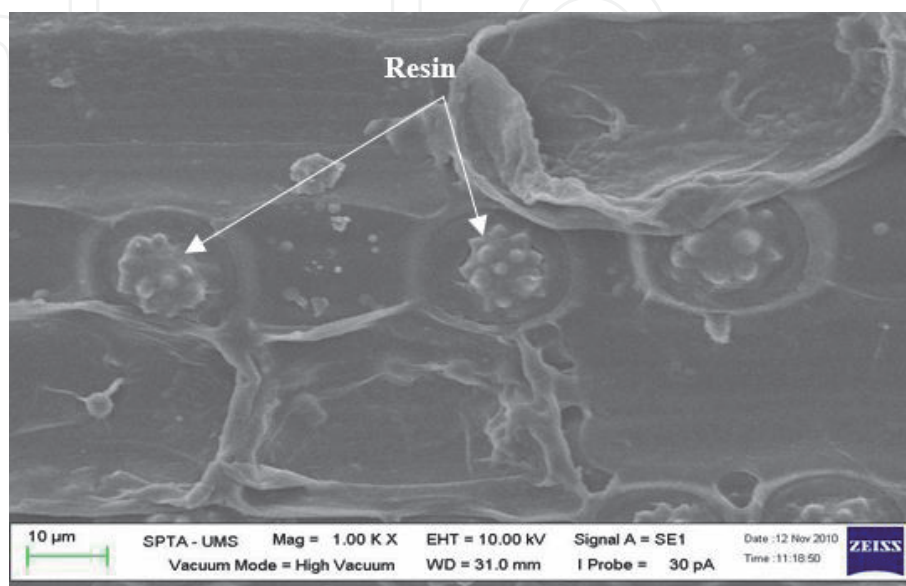


Figure 29.
SEM of resin penetration on composite board from compressed oil palm fronds (1000× magnification).

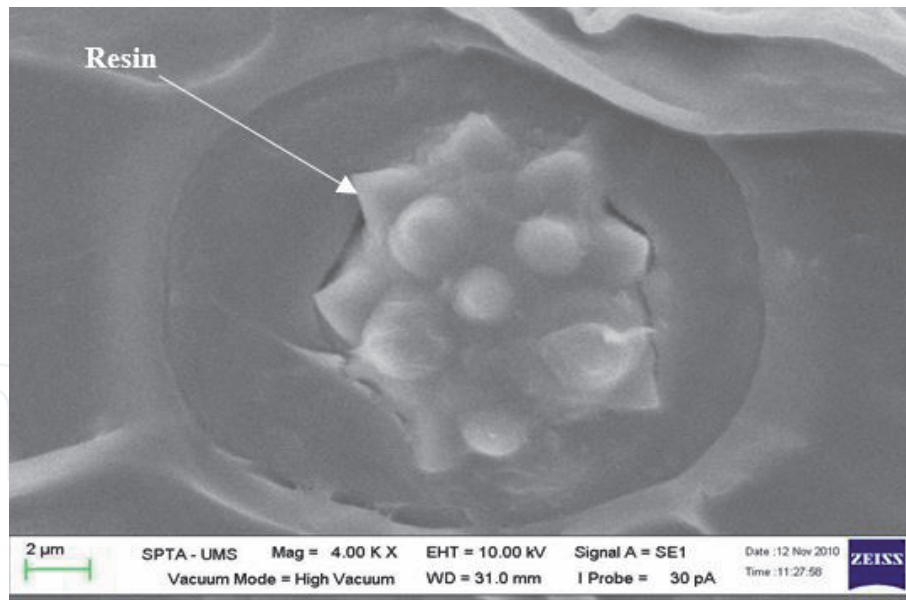


Figure 30.
SEM of resin penetration on composite board from compressed oil palm fronds (4000 × magnification).

producing this composite board did not significantly differ for density and basic density values and strength properties discussed above.

10. Conclusion

The results represent a correlation between the maturity of the oil palm frond and the portion of the oil palm fronds composite boards experimented in expressions of the physical properties and strength of the composite boards. The highest density using an air-dried method for the boards was highlighted at the matured bottom portion, followed by intermediate middle and young top portions. Besides, the density under the oven-dried method represented the values were reduced from the bottom to the top portion for each maturity group and highlighted that the mature group possessed the highest density values for every portion compared to others, followed by the intermediate and young maturity groups. Nonetheless, the MOE strength showed reduced values from the bottom to the top portion for mature level with either phenol or urea-formaldehyde resins. The MOE strength also decreased with a proportional decrease of maturity level. In addition, the MOR represented decreased value from the bottom to the top portion for each maturity level and matured to the young maturity levels for every section. The results include both types of resin used for composite board manufacturing.

Furthermore, the compression strength decreases from the bottom portion towards the middle and top section for the maturity and bottom, middle and top portions. Highlighted also the decreasing trend from mature towards intermediate and young maturity groups for the bottom portion, and this polar was also observed for the middle and top portion. Statistical analysis found significant differences between physical properties and mechanical properties across varying maturity levels and a different board section.

Finally, we can conclude that the oil palm fronds composite boards is suitable for furniture manufacturing based on physical and strength properties. The oil palm frond can produce quality composite board that possesses the physical and mechanical strength values that are better than the composite boards made from oil palm stem and less than rubberwood.

Author details

Razak Wahab^{1,2*}, Mohd Sukhairi Mat Rasat³, Norashikin Mohd Fauzi³,
Mohamad Saiful Sulaiman^{1,2}, Hashim W. Samsi⁴, Nasihah Mokhtar^{1,2},
Ros Syazmini Mohd Ghani^{1,2} and Muhammad Haziq Razak⁵

1 University College of Technology Sarawak (UCTS), Sibul, Sarawak, Malaysia

2 Centre of Excellence in Wood Engineered Products, UCTS, Sibul, Sarawak,
Malaysia

3 Universiti Malaysia Kelantan (UMK), Jeli, Kelantan, Malaysia

4 Forest Research Institute Malaysia (FRIM), Kuala Lumpur, Malaysia

5 Universiti Sains Malaysia (USM), Penang, Malaysia

*Address all correspondence to: dr Razakw5181@ucts.edu.my

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