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Effect of Moisture Content and Preservatives on the Discoloration of Oil Palm (*Elaeis guineensis* Jacq.) Lumber

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Abstract: Considering the current rate of expansion of the lumber processing industry in the world, the current annual allowable cut of one million cubic meters of round logs is considered to be insufficient to satisfy the increasing demand of timber industries. One major area that has been highlighted in the forest policy is the introduction of lesser-used species to widen the natural resource base of the forest and to address the imbalance between supply and demand for the resources. As a contribution to addressing this problem, oil palm lumber, a lesser-used species, was subjected to different moisture content variations to determine its behavior with respect to discoloration. Specimens of oil palm trunks were extracted at Norpalm Oil Mill in the Western Region of Ghana. Oil palm lumber specimens were conditioned in a kiln to a moisture content of 15%, 20%, 25%, 30%, 40%, and 50%. The results obtained covered discoloration and mold. The effect of the extractives on the discoloration of oil palm lumber was also investigated by means of immersing some samples of oil palm lumber into sea water and tap water for 48 h. Although Dursban 4E is a widely used preservative in the timber industry, oil palm lumber specimens of 40 mm thick immersed in Dursban 4E for 48 h and conditioned in a kiln to a moisture content of 30% were discolored from week 2. However, oil palm lumber specimens of 40 mm thick that were immersed in tap water for 48 h, and thereafter immersed in Dursban 4E for another 48 h, then kiln dried to a moisture content of 15%, 20%, 25%, and 30%, did not show any discoloration from week 2 to week 18. It was discovered that in the utilization of oil palm lumber, it should be immersed in tap water for 48 h before any chemical treatment is given, and thereafter kiln dried. From the general results, the species proved to be good substitute for some of the 'noble' species that are going extinct from the forests of Ghana.

Keywords: discoloration; Dursban 4E; oil palm lumber; moisture content; sea water; tap water

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1. Introduction

Oil palm (*Elaeis guineensis* Jacq.) is an important crop species with high economic benefit in the form of the export of quality palm oil [1]. Its production has increased over the last decade, resulting in an expansion of the global oil palm planting area from 10 to 17 million hectares between 2000 and 2012 [2]. It is emphasized that governments of developing and emerging countries in all the tropical regions are increasingly promoting oil palm cultivation as a major contributor to poverty alleviation, as well as food and energy independence. Oil palm is the fastest-growing global demand as input for food products, cosmetics, animal feed, bio-energy, lumber, and residual residues for the composite board industry. The oil palm tree has therefore become one of the most important non-wood lignocellulosic materials for various types of products [3,4]. It represents the most important oil crop for food and feed production and for biotechnological applications [5]. Oil palm production has brought about unlimited economic profits, and it is an emerging economic sector in Malaysia and Indonesia [6,7]. Oil palm has the lowest land use compared to over 58 million hectares of land used for soybean. Area expansion of oil palm accounts for a very small part of the total forest reserve depletion [8].

Growth of commercial plantations in North Sumatra (Indonesia) and Southeast Asia and the expansions in West Africa and Latin America has led to a growing call for the sustainability of the ever-increasing palm oil tree residues [9,10]. However, the trunks are normally left in the field without any utilization thereafter. These huge residues have become a major concern because they cause many problems and are expensive to dispose of. Hence, they are usually cut into pieces and burned, which pollutes the air and contributes to increasing CO_2 in the atmosphere [11]. Thus, enormous quantities of lignocellulosic materials are discarded in vain, while destruction of the rain forest has been expanding in the same tropical areas by excess cutting of trees [12,13]. The shortage of log supply in these areas is increasingly becoming a serious problem. Therefore, research on the utilization of oil palm trunks is on the increase.

Agro-waste from the oil palm industry such as oil palm trunks has attracted attention as a potential source for new value-added material [11,14,15]. The chemical, physical, and mechanical properties of the oil palm lumber already established indicate that this agro-waste is similar to wood, and that it may be suitable for wood-based panels, construction, furniture, and other fitments [16,17]. Many studies on the oil palm trunk also show the potential of utilizing this agricultural waste for several types of value-added products, such as high performance panel products, pulp and paper making, and animal feed [4].

The global growing demand for large diameter timber and the inability of the forest to supply implies that other lignocellulose material resources should be available for construction and manufacturing, which should help wood remain competitive against non-wood construction substitutes and stem the decline in global share in the long run [18,19]. However, wood industry workers are struggling to obtain sufficient raw materials at a competitive price. Oil palm trunk lumber is abundantly available, and it is a less expensive lignocellulosic raw material as compared to wood [4,20]. Currently, global consumption of wood is approximately 3.23 billion m^3 annually, or 0.53 m^3 per capita per year. In any case, a substantial increase in global wood demand is expected. The Food and Agriculture Organization of the United Nations (FAO), for example, recently forecast a 26% increase in industrial roundwood demand [21–23]. The increased demand is driven both by expanding economies worldwide and by population growth [24].

The oil palm tree is an emerging, non-timber forest product in the West African sub-region and the global timber industry. The grains of the oil palm look very attractive, even though it is difficult to work on. Recent studies have shown that the palm tree has the potential to be used as an alternative species to supplement timber production [4,25–27]. However, one major factor that has the potential to discourage the industry from utilizing oil palm lumber is the ease of discoloration of the products, especially at high moisture content. Preliminary research by the Malaysia Palm Oil Board demonstrated that the oil palm trunk could be engineered into palm wood. However, their results were not promising because their drying methods caused drying defects such as high degree of shrinkage, warping, checks, collapse, twisting, and discoloration with low recovery [16].

Discoloration occurs by the action of fungal stains (mold, mildew, and sap stains such as blue stain), bacterial infection (decay, rot), enzymatic (gray, some brown, etc.), and others that could be chemical, gum and resin pockets, mineral stains, and iron stains [28,29]. Hence, discoloration is the external manifestation of fungal invasion [30]. Conditions that could favor discoloration may include entry site, air/oxygen, temperature, moisture, and food source. It is therefore important to investigate the appropriate method of treating oil palm lumber of such defects in order to improve the acceptability of the product. This study, therefore, aims at determining the effective method of treating oil palm lumber to avoid the discoloration of its products.

In this study, the oil palm lumber used was processed from the large amount of agriculture waste generated during replanting by the Norpalm Oil Mills, and palm wine was extracted from them. The advantage of using these oil palm trunks was enormous: low price, readily available in large quantities, and some extractives had been removed by tapping the palm wine and leaching by raining activities. The utilization of these types of oil palm did not affect the state of the farm and the production of seedlings for the industry.

2. Materials and Methods

Materials

The main materials used for the experiment work were oil palm lumber, Dursban 4E, tap water, and sea water.

Oil palm

Forty (40)-year-old oil palm trunks were collected from a farm located in a wet, semi-deciduous forest zone in the western part of Ghana. Trunks were stout, straight, and about 550 to 610 mm in diameter. They were unproductive standing trees to be felled for a new plantation. The selected oil palm trunks were felled, and the local palm wine was tapped within 7 days, after which lengths of 4.5 m were extracted from the trunks from the bottom towards the top. These were converted into beams of dimensions 1000 mm × 320 mm × 100 mm and lumber of dimensions 1000 mm × 320 mm × 50 mm for the study. These dimensions were selected due to the size of the treatment bath.

Dursban 4E

Dursban 4E was purchased from a licensed agricultural chemical seller. This is a locally used wood preservative and contains 44.4% chlorpyrifos and 55.6% inert ingredients, with 4 pounds of chlorpyrifos per gallon. Dursban 4E was chosen due to its cost effectiveness and availability to the timber industry.

Tap water

Tap water was obtained from water supplied to homes for consumption by the Ghana Water and Sewage Company.

Sea water

The sea water for the study was obtained from the sea using buckets and drum barrels. Sea water is a solution of salt and water and contains some percentages of chloride, magnesium, sodium, calcium, sulfur, and potassium. These salts make up 99% of sea water and could act as inhibitors to the growth of discoloration fungi.

Physical characteristics of oil palm tree

Physical observation and inspection were conducted on twenty standing and twenty felled oil palm trees. The activities carried out were trunk measurement using a measuring tape and moisture content determination using a hand-held moisture meter.

Preparation of test specimens

The oil palm trunks were sawed into beams and boards, and their moisture content was determined. The moisture contents on an oven-dry basis of the oil palm lumber specimens were determined in accordance with the ASTM D 1037-06a [31]. Five samples of each of the lumber with dimensions 300 mm × 100 mm × 25 mm were placed in a laboratory oven at a temperature of 103 °C ± 2 °C. Each sample was dried until the difference in mass between two successive weighings separated by an interval of twenty-four (24) hours was 0.01 g or less. The moisture content of the specimen was then computed, as shown in Equation (1).

$$Mc\ (\%) = \frac{Fw - Ow}{Ow} \tag{1}$$

Mc = Moisture content (%)
Fw = Fresh weight (g)
Ow = Oven-dry weight (g)

The samples were immersed in preservatives for forty-eight (48) hours. The preservative was made up of 2 L of Dursban 4E and 504 L of water. The preservative-treated boards were kiln-dried to moisture contents of 20%, 30%, 40%, and 50%. Figure 1a to g shows the preparation of study specimens and Dursban 4E solution. Each of the kiln-dried specimens was repeated with five replicates.

The prepared test specimens were cut into dimensions of 300 mm × 100 mm × 40 mm (Figure 2). They were separately staked in a clean, environment-controlled room with a temperature of 25 ± 2 °C and relative humidity of 62 ± 2% for an eighteen (18)-week observation period. Pictures were taken at the end of each of the seven days using a Samsung Galaxy S9+, camera version 10.0.03.31.

Figure 1. Preparation of study specimens. (**a**) Oil palm plantation; (**b**) Converting oil palm logs into beams; (**c**) Wood-Mizer converting beams into boards; (**d**) Oil palm lumber; (**e**) Adding Dursban into water; (**f**) Immersion of oil palm lumber into preservative; (**g**) Dursban 4E.

Figure 2. Specimens for observation in 18 weeks.

Determination of chemical composition (*Cellulose*, *Holocellulose*, and *Lignin*)

Cellulose, hemicellulose, and lignin contents of oil palm lumber specimens were analyzed via acid detergent fiber (ADF), neutral detergent fiber (NDF), and acid detergent lignin (ADL) methods [32,33].

During NDF analysis, approximately 1.0 g of dried oil palm lumber specimens were transferred into a round-bottomed flask connected with a condensing unit, followed by 100 mL of preheated neutral detergent solution (30 g of sodium lauryl sulphate, 18.61 g of EDTA disodium salt, 6.81 g of sodium borate decahydrate, 4.56 g of disodium hydrogen phosphate, and 10 mL of 2-ethoxy ethanol dissolved in 1 L of distilled water). After the mixture was heated for 1 h at its boiling temperature, the solution was cooled down to room temperature and filtered. The residue was washed three times with hot, distilled water, followed by washing three times with acetone, and then vacuum dried. Further drying was conducted at 105 °C for 3 h. The percentage of weight loss was calculated from the initial and final weight differences.

The ADF analysis was similar to that of NDF but used a different detergent solution, which was acid detergent solution. (An amount of 20 g acetyl trimethylammonium bromide was dissolved in 700 mL of distilled water, and 27.56 mL of 96.7% sulphuric acid was then added to the solution and then topped up to 1 L with distilled water).

The ADL analysis was started by covering the residues from the ADF analysis with 72% H_2SO_4 (15 °C) solution and stirred three times at hourly intervals. The mixture was then filtered, washed with hot water, dried at 105 °C for 3 h, and then cooled down to room temperature. The residue was heated in a furnace set at a temperature of 500 °C for 2 h. The still-hot crucibles were then transferred into a 100 °C oven for an hour before being cooled in a desiccator to room temperature and then weighed. The percentage of weight loss was calculated from the initial and final weight differences.

The percentages of cellulose, hemicelluloses, and lignin were then calculated using the Equations (2)–(4).

$$\text{Cellulose (\%)} = \text{ADF} - \text{ADL} \tag{2}$$

$$\text{Hemi-cellulose (\%)} = \text{NDF} - \text{ADF} \tag{3}$$

$$\text{Lignin (\%)} = \text{ADL} \tag{4}$$

Testing of Specimens

The specimens were staked on dried, hard wooden strips to prevent them from coming in direct contact with the floor and each other. The space between each sample was 150 mm to allow enough air circulation and space for observation. Considering the degree of comfort for a human object, the temperature of the testing environment was set at 25 ± 2 °C, and the relative humidity was set at 62 ± 5%.

Determination of mold in oil palm lumber

Visual inspection was used mainly to observe the occurrence of molds on the surfaces of the test specimens. This was repeated every week, and pictures were taken for the final appearance at the end of the study period.

3. Results and Discussion

3.1. Physical Characteristics Identified in the Study

The oil palm trunks were stout, straight, about 304 mm to 610 mm in diameter, and grew about 460 to 920 mm. Oil palms can reach 18.29 to 24.38 m in height in nature, but they are rarely more than 6.10 or 9.14 m in cultivation. The trunks of oil palm trees contain mineral salts, notably silica, with high cutting tool edge recession. Hence, cutting tools made from high-speed steel (HSS) would be the most suitable tools for machining wood samples of the oil palm.

3.2. Moisture Content (MC)

The average MC in the fresh condition after cutting is 402.78%. The MC in the wood is about 30–300% [34]. However, it cannot be generalized because there are many factors, such as species and environment. In this study, oil palms recorded high MC because logging was performed during the rainy season. High MC can be influenced by the presence of parenchymal tissues that dominate the oil palm trunk [35]. These tissues are known for absorbing and storing water very well [27]. The results of this study indicate that oil palm trunks contain high MC, which confirms the results of other research works [26,35].

3.3. Chemical Composition of Oil Palm Lumber

The chemical constituents of oil palm trunk lumber are outlined in Table 1.

Table 1. Chemical composition of oil palm trunk lumber.

Chemical Constituents	Composition (%)	Standard Deviation
Cellulose	42.90	2.92
Hemicellulose	26.35	1.41
Lignin	19.26	0.86
Starch *	82.07	01.5

* Source: [36,37].

Starch content is extremely high in the parenchyma [4,37,38]. This is the reason why fungi grow so fast on the surface of the cross section of oil palm trunks. Hence, due to the high content of sugar and starch in the oil palm stem, it is very susceptible to fungi and termites [35,39].

The lignin content is low in comparison to ordinary wood. The low lignin content and relatively high carbohydrate content of oil palm trunk lumber imply that this wood can be useful for the production of fiberboards. Utilization of oil palm trunk lumber for the production of fiberboards and plywood were reported by [4] and [40].

Several attempts to utilize oil palm trunks as building and construction materials have also been reported by [41] and [42]. Long-shaped vascular bundles themselves can be used as raw material for veneer and wood-based panels, such as cement boards, fiberboards, and strand boards [43]. The outer region near the bark is rich in vascular bundles, and the density of this area is high. Therefore, the outer region might be appropriate for manufacturing building materials. However, the inner region, with low lignin content and high parenchyma content in the tissue structure, is not suited for building materials, which requires strength to a significantly greater extent [44,45].

Experimental results are presented in Figures 3 and 4. Immersion of the samples of oil palm lumber into fresh water for 48 h followed by immersion into Dursban 4E solution for 48 h before kiln drying did not produce any discoloration on the surfaces of the samples. Similarly, the immersion of the samples of oil palm lumber into sea water for 48 h followed by immersion into Dursban solution for 48 h before kiln drying did not produce any discoloration on the surfaces of the samples.

Figure 4 shows images of the original oil palm wood surfaces after they were immersed in tap water for 48 h, and thereafter immersed in Dursban 4E for another 48 h, after which the samples were conditioned in a kiln. It can be clearly observed that oil palm lumber surfaces were all clear, having no discoloration for all the moisture contents and at the 18-week duration. Tap water caused the disruption of sugar and starch pathways in the palm wood, which could have been the food for the discoloration fungi. This is because during the immersion of oil palm lumber, sugar and starch on the surfaces were washed quickly, and the water prevented the migration, deposition, and concentration of sugar and starch at the surface. Similar results were reported in other studies: in their study, [46] observed that water reduced surface discoloration. In contrast, discoloration was reported to be present at the wood's surface by [47]. Ref. [48] emphasized that wood specimens treated with water greatly reduced the levels of fatty acids without any visual discoloration to the wood specimens. Ref. [49] used water to alleviate discoloration in wood. Ref. [50] highlighted that an effective method of eliminating wood biodeterioration attacks is to use water. The authors further recommended an approved Dursban application as the best.

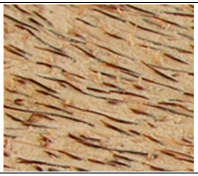
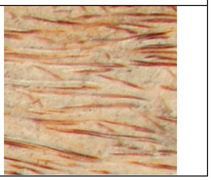
Weeks	Moisture Content (MC) (%)			
	20	30	40	50
1				

Figure 3. *Cont.*

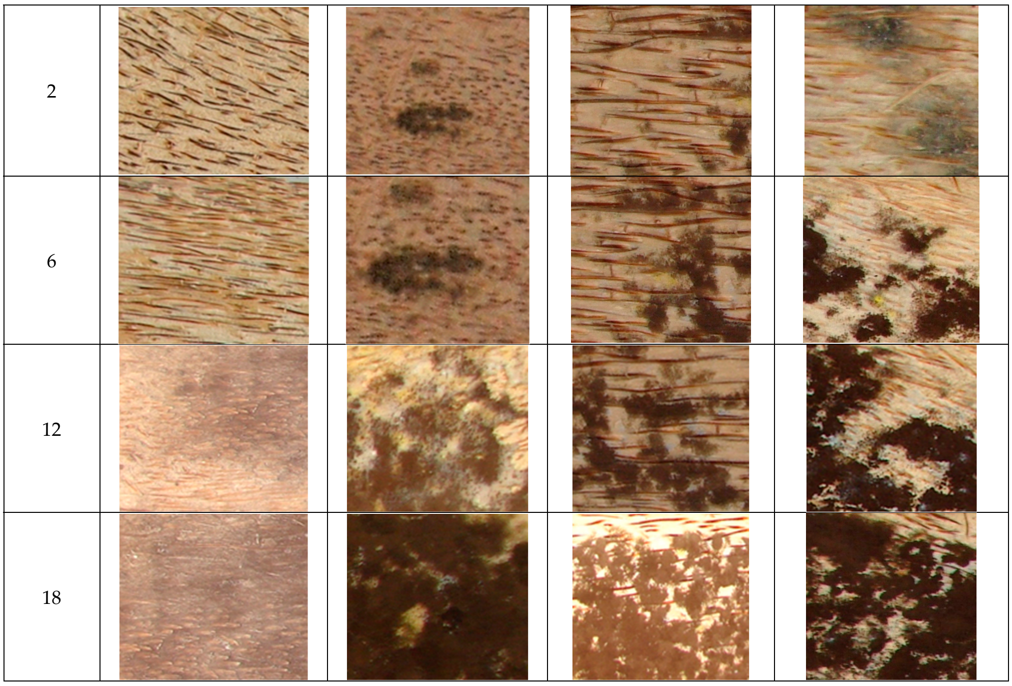


Figure 3. Surface color of oil palm samples immersed in tap water for 48 h, and thereafter conditioned in a kiln to varying MCs at a thickness of 40 mm. These results indicate that at a higher MC, discoloration increases with an increase in duration.

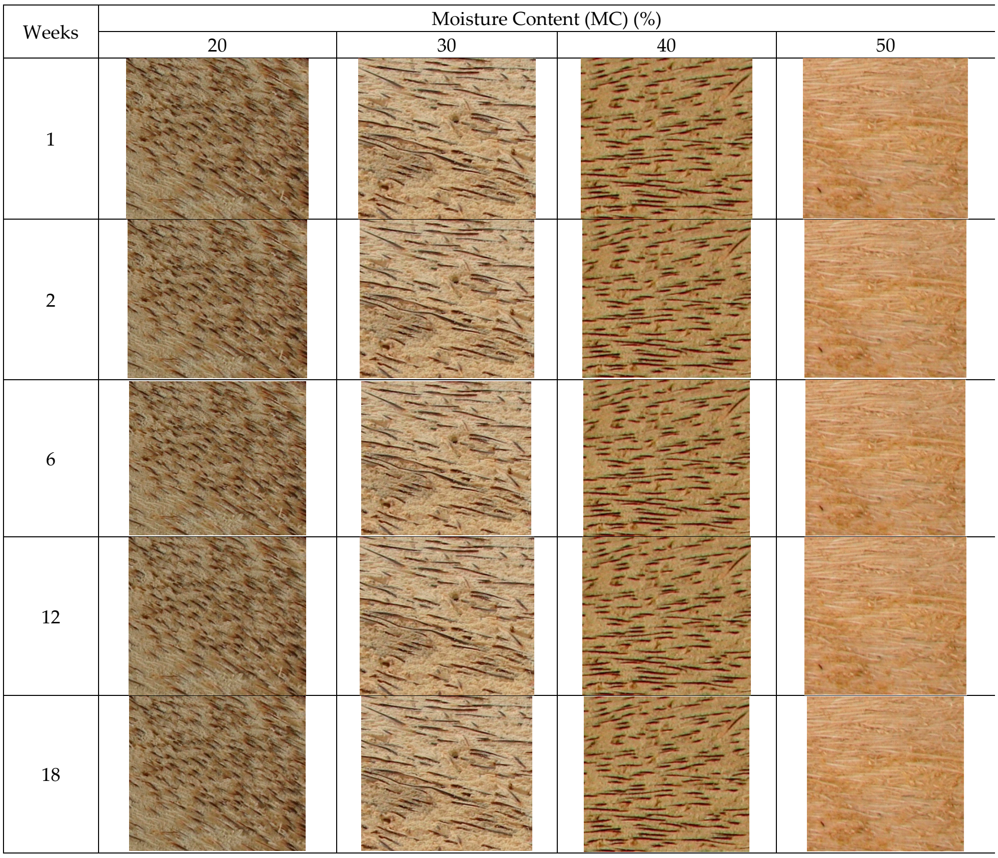


Figure 4. The surface color of oil palm samples immersed in tap water for 48 h, and thereafter immersed in Dursban 4E for another 48 h, after which the samples were conditioned in a kiln to varying moisture contents at a thickness of 40 mm. There was no significant change in the color of the specimens during the eighteen weeks of observation.

The results of this work showed that the color around the fungal colony changed during the 18 weeks of observation (Figures 3 and 5a).

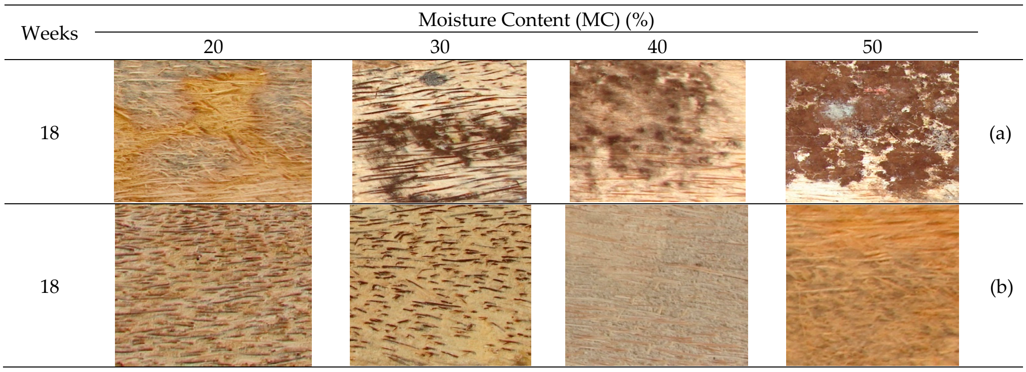


Figure 5. (**a**) The result indicated that in week 18, oil palm specimens at 20% MC immersed in sea water only for 48 h and thereafter conditioned in a kiln, exhibited a significant discoloration which increased with an increased in percentage MC in the oil palm specimens. (**b**) Whereas those specimens immersed in sea water for 48 h, followed by immersion into Dursban 4E for 48 h, and thereafter conditioned in a kiln to varying MCs did not exhibit any discoloration.

The result indicated that in week 18, oil palm specimens at 20% MC immersed in sea water only for 48 h and thereafter conditioned in a kiln, exhibited a significant discoloration which increased with an increased in percentage MC in the oil palm specimens. Whereas those specimens immersed in sea water for 48 h, followed by immersion into Dursban 4E for 48 h, and thereafter conditioned in a kiln to varying MCs did not exhibit any discoloration (Figure 5).

The oil palm tree trunk is very hygroscopic, which means it shrinks and swells easily upon the loss and gain of water, respectively. This hygroscopic property could improve the absorption of water, which could result in the removal of some sap to give way to the entrance of the preservative material during immersion to crystalize the sugar and render it poisonous to the deteriorating organisms.

Comparatively, specimens immersed in sea water only for 48 h, and thereafter conditioned in a kiln to varying moisture contents at a thickness of 40 mm showed visible discoloration at all the MC levels. Specimens immersed in sea water for 48 h, followed by immersion into Dursban 4E for 48 h, and thereafter conditioned in a kiln to varying moisture contents at a thickness of 40 mm showed no visible discoloration at any of the MC levels (Figure 5). However, oil palm lumber specimens of 40 mm thick immersed in Dursban 4E for 48 h and conditioned in a kiln to a moisture content of 30% discolored from week 2.

Legend A: The surface color of oil palm specimens immersed in sea water only for 48 h, and thereafter conditioned in a kiln to varying MCs at a thickness of 40 mm.

Legend B: The surface color of oil palm specimens immersed in sea water for 48 h, followed by immersion into Dursban 4E for 48 h, and thereafter conditioned in a kiln to varying MCs at a thickness of 40 mm.

Oil palm logs, and for that matter, oil palm lumber, attract infestation of both insects and fungi fairly quickly (some even happened overnight) when they are left in the field or even under cover (personal observations by the authors). The high susceptibility of oil palm stems and boards to infestation by both fungi and insects is due to the presence of high sugar and starch in the parenchyma cells [51,52]. Thus, the lumber should immediately be immersed into pure water after being sawed, before preservatives are applied. [47] concluded in their study on the anatomical characterization and utilization of oil palm wood that oil palm wood from the outer zone of the trunk provides the best properties. Even so, that part of oil palm wood has at least four imperfections that need to be improved: (1) very low in strength; (2) very bad in durability; (3) very low dimensional stability; and (4) very poor machining characteristics. The results of this study, therefore, confirm the results of [47]. Although the oil palm wood vinegar produced exhibited antifungal and antitermite activities against white-rot fungus, *Trametes versicolor,* brown-rot fungus, and *Fomitopsis palustris* [53], the treatment processes outlined in the study were the impetuses for the growth inhibition of discoloration of oil palm lumber.

Bakar et al. [47], indicated that the outer zones of the trunk have better quality than those from the inner zones, and that the outer zones can be used as solid wood after proper treatment. Hence, properly treated oil palm lumber can be used for producing cabinet, cladding, furniture, other fitments and carving works.

Discolorations and stains usually create an objectionable color or appearance of the lumber. Chemical treatment can enhance the resistance of palm wood. The chemical treatment of oil palm lumber showed a high resistance against dry wood termites. Tap water and Dursban played an important role in eliminating the discoloration effects on the lumber. They acted as a preservative in the oil palm lumber. After being chemically treated, discoloration was not observed in the lumber after 18 weeks. Therefore, this application (the use of water, Dursban, and kiln drying) exhibited the best resistance against discoloration, compared to other applications [47,54]

3.4. Mold as Occurred in Oil Palm Lumber Specimens

It was observed that mold was not capable of degrading the structural components of oil palm lumber. Unlike decaying fungi, mold-causing fungi did not tunnel through the lumber but lived only on the surface [55,56]. Further revelation indicates that mold fungi often flourish when excessive water is present. Hence, dampness and inadequate ventilation typically result in the growth of mold on oil palm lumber surfaces. The growth of mold leaves the affected specimens of oil palm lumber discolored to black, as shown in Figure 6. [57] emphasized that oil palm lumber experiences photo-degradation upon exposure to water and sunlight, especially ultraviolet (UV). However, it has been reported that UV light cannot penetrate deeper than 75 µm, though degradation occurs deeper than this in combination with other factors [58]. Hence, the material climate is determined by wood moisture content, temperature, and their dynamics [59].

Figure 6. Mildew grows on the surface of the oil palm lumber and discolors the affected specimen to black.

Lim and Khoo identified that the moisture content in oil palms increases with the increasing amount of parenchyma tissue from the periphery to the center and from the stem base to the top until 400% [60]. Parenchyma cells are a suitable substrate for many microorganisms [61]. Therefore, as with other lignocelluloses, the felled trunk, with its high parenchyma and moisture content, is susceptible to the colonization by mildew fungi until the wood has dried down below the fiber saturation of approximately 30% moisture content. Mold-infected products are not accepted by the consumers, and rot reduces wood strength properties.

4. Conclusions

This study aimed to determine the effective method of treating oil palm lumber to avoid the discoloration of its products. The oil palm lumber immersed in tap water for 48 h, and thereafter immersed in a preservative solution of Dursban 4E, completely inhibited the growth of discoloration, whereas the specimens that were not immersed in tap water and Dursban 4E discolored. The practical utilization of either tap water or sea water mixed with Dursban 4E as oil palm lumber preservatives using immersion is worthy of consideration. This study has demonstrated that discoloration on the surface of oil palm products can be avoided if treated with either sea water or tap water mixed with Dursban 4E preservatives before kiln drying.

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References

1. Yurnaliza, Y.; Jamilah, I.; Hartanto, A.; Lutfia, A. Screening of endophytic fungi from oil palm (Elaeis guineensis) in producing exopolysaccharides. *Biodiversitas J. Biol. Divers.* **2021**, *22*, 1467–1473. [CrossRef]
2. Pirker, J.; Mosnier, A.; Kraxner, F.; Havlík, P.; Obersteiner, M. What are the limits to oil palm expansion? *Glob. Environ. Chang.* **2016**, *40*, 73–81. [CrossRef]
3. Mhd Ramle, S.F.; Sulaiman, O.; Hashim, R.; Arai, T.; Kosugi, A.; Abe, H.; Mori, Y. Characterization of Parenchyma and Vascular. *Lignocellul. J.* **2012**, *1*, 33–44.
4. Sulaiman, O.; Salim, N.; Nordin, N.A.; Hashim, R.; Ibrahim, M.; Sato, M. The potential of oil palm trunk biomass as an alternative source for compressed wood. *BioResources* **2012**, *7*, 2688–2706. Available online: http://ncsu.edu/bioresources (accessed on 19 September 2022). ISSN: 1930-2126. [CrossRef]
5. Gutbrod, P.; Reichert, S.; Gutbrod, K.; Hamai, A.; Bréhélin, C.; Ngando-Ebongue, G.; Dörmann, P. Fatty acid isoprenoid alcohol ester synthesis in fruits of the African Oil Palm (Elaeis guineensis). *Phytochemistry* **2021**, *185*, 112684. Available online: https://hal.archives-ouvertes.fr/hal-03141513/document (accessed on 29 July 2022). [CrossRef]
6. Susila, W.R. Contribution of Oil Palm Industry To Economic Growth and Poverty Alleviation in Indonesia. *J. Litbang Pertan.* **2004**, *23*, 107–114.
7. Alam, A.S.A.F.; Er, A.C.; Begum, H. Malaysian Oil Palm Industry: Prospect and Problem. *J. Food Agric. Environ.* **2015**, *13*, 143–148.
8. Levin, J. Profitability and Sustainability in Palm Oil Production Analysis. In *Analysis of Incremental Financial Costs and Benefits of RSPO Compliance*; WWF Report; WWF-US, FMO, CDC: Westernieland, Netherlands, 2012.
9. Mirande-Ney, C.; Tcherkez, G.; Balliau, T.; Zivy, M.; Gilard, F.; Cui, J.; Ghashghaie, J.; Lamade, E. Metabolic leaf responses to potassium availability in oil palm (*Elaeis guineensis* Jacq.) trees grown in the field. *Environ. Exp. Bot.* **2020**, *175*, 104062. [CrossRef]
10. Hansen, S.B.; Padfield, R.; Syayuti, K.; Evers, S.; Zakariah, Z.; Mastura, S. Trends in global palm oil sustainability research. *J. Clean. Prod.* **2015**, *100*, 140–149. [CrossRef]
11. Kpalo, S.Y.; Zainuddin, M.F.; Manaf, L.A.; Roslan, A.M. Evaluation of hybrid briquettes from corncob and oil palm trunk bark in a domestic cooking application for rural communities in Nigeria. *J. Clean. Prod.* **2020**, *284*, 124745. [CrossRef]
12. Tomimura, Y. Chemical characteristics and utilization of oil palm trunks. *Jpn. Agric. Res. Q. JARQ* **1992**, *25*, 283–288.
13. Zeng, N.; Hausmann, H. Wood Vault: Remove atmospheric CO2 with trees, store wood for carbon sequestration for now and as biomass, bioenergy and carbon reserve for the future. *Carbon Balance Manag.* **2022**, *17*, 1–29. [CrossRef] [PubMed]
14. Asyraf, M.R.M.; Ishak, M.R.; Syamsir, A.; Nurazzi, N.M.; Sabaruddin, F.A.; Shazleen, S.S.; Razman, M.R. Mechanical properties of oil palm fibre-reinforced polymer composites: A review. *J. Mater. Res. Technol.* **2021**, *17*, 33–65. [CrossRef]
15. Sanyang, M.L.; Sapuan, S.M.; Jawaid, M.; Ishak, M.R.; Sahari, J. Recent developments in sugar palm (Arenga pinnata) based biocomposites and their potential industrial applications: A review. *Renew. Sustain. Energy Rev.* **2016**, *54*, 533–549. [CrossRef]
16. Abdul-Khalil, H.P.S.; Bhat, A.H.; Jawaid, M.; Amouzgar, P.; Ridzuan, P.; Said, M.R. Agro-Waste: Mechanical and Physical Properties of Resin Impregnated Oil Palm Trunk Core Lumber. *Polym. Compos.* **2010**, *31*, 638–644. [CrossRef]

17. Okai, R.; Mitchual, S.J.; Mensah, P.; Dzakpasu, R.K. Characterization of Physical, Machining and Finishing Properties of Oil Palm Lumber: An Emerging Non-Timber Forest Product in Sub-Saharan Africa. *Int. J. Emerg. Technol. Adv. Eng.* **2015**, *5*, 289–296.
18. Chen, C.; Kuang, Y.; Zhu, S.; Burgert, I.; Keplinger, T.; Gong, A.; Li, T.; Berglund, L.; Eichhorn, S.J.; Hu, L. Structure–property–function relationships of natural and engineered wood. *Nat. Rev. Mater.* **2020**, *5*, 642–666. [CrossRef]
19. Wear, D.N.; Prestemon, J.; Foster, M.O. US Forest Products in the Global Economy. *J. For.* **2016**, *114*, 483–493. [CrossRef]
20. Shamsudin, N.A.; Sahid, I.; Mokhtar, A.; Muhamad, H.; Ahmad, S. Life cycle inventory of oil palm lumber production: A gate-to-gate case study. In *AIP Conference Proceedings*; AIP Publishing LLC: Melville, NY, USA, 2018; Volume 1940, p. 020042. [CrossRef]
21. Mantau, U.; Saal, U.; Prins, K.; Steierer, F.; Lindner, M.; Verkerk, H.; Eggers, J.; Leek, N. *EUwood-Real Potential for Changes in Growth and Use of EU Forest*; Final Report; Hamburg/Germany, 2010; p. 160. Available online: https://franzjosefadrian.com/wp-content/uploads/2013/06/euwood_final_report.pdf (accessed on 19 September 2022).
22. Warman, R.D. Global wood production from natural forests has peaked. *Biodivers. Conserv.* **2014**, *23*, 1063–1078. [CrossRef]
23. Whiteman, A.; Brown, C. Modelling global forest products supply and demand: Recent results from FAO and their potential implications for New Zealand. *N. Z. J. For.* **2000**, *44*, 6–9.
24. Bowyer, J.L.; Stockmann, V.E. Agricultural Residues. An Exciting Bio-Based Raw Material for the Global Panel Industry. 2017. Available online: https://www.researchgate.net/publication/279546173. (accessed on 29 July 2022).
25. Alotaibi, M.D.; Alshammari, B.A.; Saba, N.; Alothman, O.Y.; Sanjay, M.R.; Almutairi, Z.; Jawaid, M. Characterization of natural fiber obtained from different parts of date palm tree (*Phoenix dactylifera* L.). *Int. J. Biol. Macromol.* **2019**, *135*, 69–76. [CrossRef] [PubMed]
26. Iswanto, A.H.; Sucipto, T.; Azhar, I.; Coto, Z.; Febrianto, F. Physical and mechanical properties of oil palm stem (Elaeis guineensis Jacq.) From Aek Pancur garden in North Sumatra (in Indonesian). *Jurnal Ilmu dan Teknologi Hasil Hutan* **2010**, *3*, 1–7.
27. Rafidah, J.; Asma, W.; Puad, E.; Mahanim, S.M.A.; Shaharuddin, H. *Toward Zero Waste Production of Value-Added Products from Waste Oil Palm Trunk (WOPT)*; Forest Research Institute Malaysia (FRIM): Kuala Lumpur, Malaysia, 2012. [CrossRef]
28. Ilango, P.; Arulpari, M.; Medona, M.; Abirami, T. Chlorhexidine: A miracle chemical. *Int. J. Curr. Res. Rev.* **2013**, *5*, 26–34.
29. Rahman, M.A.; Fuad, A. *Biodeterioration of Wood By Fungi*; Forestry and Wood Technology Discipline Khulna University Khulna: Khulna, Bangladesh, 2002; pp. 20–38. Available online: https://d1wqtxts1xzle7.cloudfront.net/63734494/Biodeterioration_of_Wood_by_Fungi_-_MS_Project_Thesis_xii__65_pages_as_pdf20200624-8910-1x5imij-libre.pdf?1593109007=&response-content-disposition=inline%3B+filename%3DBIODETERIORATION_OF_WOOD_BY_FUNGI_Forest.pdf&Expires=1666191875&Signature=e3jt1VTmSDZzZ6~{}fJ7efn9NjzoGWG0FWciMEd1pXKUfGuCMMLNlbR97AiNVoCN8sa0R7oXlXghLWbuLhSAyoMLzxfERm9nUxAU7zme4r9eoQfOoSTqM~{}U4NltMUKQFlbMetqsCiWoWBAcMBP1wfc0HoGkvfG1MzlclGBTRIEdZ8hV61DPVC2gkZHOnSdQ~{}zk8wCVz3PeB7EqQ4EUXOnIa8okumQRbH9cTRboVt12StImA7lZAuG28FlpCE9HvD6A9fPeDE~{}sYT~{}mzX6wmrVFJxEFTFeG8Myw2WdbvmbWNkX4ofhfPHHwLp9eTJuXS2qJFgsl7W~{}pNLs98Yspl0Gjqg__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA (accessed on 29 July 2022).
30. Rees, R.W.; Flood, J.; Hasan, Y.; Potter, U.; Cooper, R.M. Basal stem rot of oil palm (Elaeis guineensis); mode of root infection and lower stem invasion by Ganoderma boninense. *Plant Pathol.* **2009**, *58*, 982–989. [CrossRef]
31. ASTM International. *Standard Test Methods for Evaluating Properties of Wood-Base Fibre and Particle Panel Materials*; ASTM standard D1037-06a; ASTM: Philadelphia, PA, USA, 1999.
32. Omar, R.; Idris, A.; Yunus, R.; Khalid, K.; Isma, M.A. Characterization of empty fruit bunch for microwave-assisted pyrolysis. *Fuel* **2011**, *90*, 1536–1544. [CrossRef]
33. Shi, K.; Oladejo, J.M.; Yan, J.; Wu, T. Investigation on the interactions among lignocellulosic constituents and minerals of biomass and their influences on co-firing. *Energy* **2019**, *179*, 129–137. [CrossRef]
34. Tsoumis, G. *Science and Technology of Wood: Structure, Properties, Utilization*; Van Nostrand Reinhold: New York, NY, USA, 1991; Volume 115.
35. Bahanawan, A.; Kusumah, S.S.; Darmawan, T.; Ismadi; Masruchin, N.; Sudarmanto; Jayadi; Pramasari, D.A.; Triwibowo, D.; Kusumaningrum, W.B.; et al. Moisture Content, Color Quantification and Starch Content of Oil Palm Trunk (*Elaeis guineensis* Jack.). *Earth Environ. Sci.* **2019**, *374*, 012041. [CrossRef]
36. Sulaiman, N.S.; Hashim, R.; Amini MH, M.; Sulaiman, O.; Hiziroglu, S. Evaluation of the properties of particleboard made using oil palm starch modified with epichlorohydrin. *BioResources* **2013**, *8*, 283–301. [CrossRef]
37. Salleh, K.M.; Hashim, R.; Sulaiman, O.; Hiziroglu, S.; Nadhari, W.N.A.W.; Karim, N.A.; Jumhuri, N.; Ang, L.Z.P. Evaluation of properties of starch-based adhesives and particleboard manufactured from them. *J. Adhes. Sci. Technol.* **2014**, *29*, 319–336. [CrossRef]
38. H′ng, P.; Wong, L.; Chin, K.L.; Tor, E.; Tan, S.; Tey, B.T.; Maminski, M. Oil palm (Elaeis guineensis) trunk as a resource of starch and other sugars. *J. Appl. Sci.* **2011**, *11*, 3053–3057. [CrossRef]
39. Loh, Y.F.; Paridah, T.; Hoong, Y.B.; Bakar, E.S.; Anis, M.; Hamdan, H. Resistance of phenolic-treated oil palm stem plywood against subterranean termites and white rot decay. *Int. Biodeterior. Biodegrad.* **2011**, *65*, 14–17. [CrossRef]
40. Rosli, F.; Ghazali, C.M.R.; Abdullah, M.M.A.B.; Hussin, K. A review: Characteristics of oil palm trunk (OPT) and quality improvement of palm trunk plywood by resin impregnation. *BioResources* **2016**, *11*, 5565–5580. [CrossRef]

41. Dungani, R.; Jawaid, M.; Khalil, H.A.; Jasni, J.; Aprilia, S.; Hakeem, K.R.; Islam, M.N. A review on quality enhancement of oil palm trunk waste by resin impregnation: Future materials. *BioResources* **2013**, *8*, 3136–3156. Available online: http://ncsu.edu/bioresources (accessed on 19 September 2022). ISSN: 1930-2126. [CrossRef]
42. Abram, N.K.; Xofis, P.; Tzanopoulos, J.; MacMillan, D.C.; Ancrenaz, M.; Chung, R.; Ambu, L. Synergies for improving oil palm production and forest conservation in floodplain landscapes. *PLoS ONE* **2014**, *9*, e95388. [CrossRef]
43. Loh, Y.F.; Paridah, T.; Hoong, Y.B.; Yoong, A.C.C. Effects of treatment with low molecular weight phenol formaldehyde resin on the surface characteristics of oil palm (Elaeis guineensis) stem veneer. *Mater. Des.* **2011**, *32*, 2277–2283. [CrossRef]
44. Klímek, P.; Wimmer, R.; Meinlschmidt, P.; Kúdela, J. Utilizing Miscanthus stalks as raw material for particleboards. *Ind. Crop. Prod.* **2018**, *111*, 270–276. [CrossRef]
45. Nuryawan, A.; Sutiawan, J.; Rahmawaty; Masruchin, N.; Bekhta, P. Panel Products Made of Oil Palm Trunk: A Review of Potency, Environmental Aspect, and Comparison with Wood-Based Composites. *Polymers* **2022**, *14*, 1758. [CrossRef]
46. Xie, Y.; Krause, A.; Militz, H.; Mai, C. Weathering of uncoated and coated wood treated with methylated 1, 3-dimethylol-4, 5-dihydroxyethyleneurea (mDMDHEU). *Holz als Roh-und Werkst.* **2008**, *66*, 455–464. [CrossRef]
47. Bakar, E.S.; Hamzah, N.N.; Ashaari, Z.; Hua, L.S. Assessment of oil palm wood quality improvement through integrated treatment process as function of sawing pattern and slab thickness. *J. Oil Palm Res.* **2017**, *29*, 366–372. [CrossRef]
48. Burnes, T.A.; Blanchette, R.A.; Farrell, R.L. Bacterial biodegradation of extractives and patterns of bordered pit membrane attack in pine wood. *Appl. Environ. Microbiol.* **2000**, *66*, 5201–5205. [CrossRef]
49. Sandoval Torres, S.; Jomaa, W.; Puiggali, J.R.; Avramidis, S. Multiphysics modeling of vacuum drying of wood. *Appl. Math. Model.* **2011**, *35*(10), 5006–5016. [CrossRef]
50. Zak, B. *A Field Guide to Texas Critters: Common Household and Garden Pests*; Taylor Trade Publishing: Abingdon, UK, 1988.
51. Yamada, H.; Tanaka, R.; Sulaiman, O.; Hashim, R.; Hamid, Z.; Yahya, M.; Kosugi, A.; Arai, T.; Murata, Y.; Nirasawa, S.; et al. Old oil palm trunk: A promising source of sugars for bioethanol production. *Biomass Bioenergy* **2010**, *34*, 1608–1613. [CrossRef]
52. Zahari, M.A.K.M.; Zakaria, M.R.; Ariffin, H.; Mokhtar, M.N.; Salihon, J.; Shirai, Y.; Hassan, M.A. Renewable sugars from oil palm frond juice as an alternative novel fermentation feedstock for value-added products. *Bioresour. Technol.* **2012**, *110*, 566–571. [CrossRef]
53. Oramahi, H.A.; Yoshimura, T.; Diba, F.; Setyawati, D.; Nurhaida. Antifungal and Antitermitic activities of wood vinegar from Oil palm trunk. *J. Wood Sci.* **2018**, *64*, 311–317. [CrossRef]
54. Akinlabi, E.T.; Anane-Fenin, K.; Akwada, D.R. Regeneration, cultivation, and sustenance of bamboo. In *Bamboo*; Springer: Cham, Switzerland, 2017; pp. 39–86. [CrossRef]
55. Sandberg, D.; Kutnar, A.; Karlsson, O.; Jones, D. *Wood Modification Technologies: Principles, Sustainability, and the Need for Innovation*; CRC Press: Boca Raton, FL, USA, 2021. [CrossRef]
56. Wong, R. Green possibilities in a green industrial sector: The lumber industry. *Phys. Sci. Rev.* **2020**, *5*. [CrossRef]
57. Geburtig, A.; Wachtendorf, V. Determination of the spectral sensitivity and temperature dependence of polypropylene crack formation caused by UV-irradiation. *Polym. Degrad. Stab.* **2010**, *95*, 2118–2123. [CrossRef]
58. Hon, D.N.-S.; Shiraishi, N. (Eds.) Weathering and photochemistry of wood. In *Wood and Cellulose Chemistry*; Marcel Dekker: New York, NY, USA, 2001; pp. 512–546.
59. Gobakken, L.R.; Lebow, P.K. Modelling mould growth on coated modified and unmodified wood substrates exposed outdoors. *Wood Sci. Technol.* **2009**, *44*, 315–333. [CrossRef]
60. Lim, S.C.; Khoo, K. Characteristics of oil palm trunk and its potential utilization. *Malays. For.* **1986**, *49*, 3–22.
61. Schmidt, O. Wood and Tree Fungi. In *Biology, Damage, Protection, and Use*; Springer: Berlin, Germany, 2006; pp. 119–133.