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Review

Thermal treatment of wood using vegetable oils: A review

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HIGHLIGHTS

- Effects of oil heat treatment on wood are reviewed.
- Advantages and disadvantages of using vegetables are discussed.
- Different types of treatment procedures are compared.
- Factors governing the treatment effectiveness are listed.
- Potential applications of oil heat treated wood are discussed.

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ABSTRACT

Wood is an ideal building material as it is renewable and green. However, low dimensional stability and durability might restrict its usage in structural application. Therefore, modification is needed to improve the aforementioned issues. As an environmentally friendly wood modification method, heat treatment of wood using oil as a heating medium has brought to researcher's attention to the fact that it might serve as an excellent treatment procedure in treating wood. This paper presents a review about the effects of oil heat treatment on the properties of wood such as colour stability, dimensional stability, mechanical strength and durability against termites and fungi as well as its potential to be used as construction and building materials. The pros and cons of using oil as a heating medium in wood treatment are discussed. This review shows discrepancies between the treatment methods or procedures and its resultant findings. Moreover, the effectiveness of the treatment is governed by several factors such as the type of oils used and wood species. The objective of the present paper is to conduct a review of the published literatures regarding the properties of wood modified by oil heat treatment and the results obtained were compared systematically.

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Contents

1. Introduction . . . 409
2. Advantages and disadvantages of using oil as heating medium . . . 409
3. Different types of oil heat treatment . . . 410
4. Factors that influence the effectiveness of oil heat treatment . . . 410
   4.1. Oil type . . . 410
   4.2. Treatment parameter and procedure . . . 411
   4.3. Wood anatomy . . . 412
5. Effect of oil heat treatment on the properties of wood . . . 412
   5.1. Colour changes . . . 412

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5.2. Dimensional stability . . . 413
5.3. Mechanical properties . . . 413
5.4. Durability against biodeterioration agents . . . 414
6. Comparison between OHT and other heat treatment methods . . . 416
7. Potential applications of oil heat treated wood . . . 416
8. Conclusions . . . 417
Conflict of interest . . . 417
Acknowledgements . . . 417
References . . . 417

1. Introduction

As a renewable lignocellulosic material, wood is an ideal building material that is easy to work with and offers advantages such as high strength-to-weight ratio and lower processing energy. Unfortunately, dimensional instability is one of the major shortcomings of wood compared with synthetic materials coming from non-renewable resources. Dimensional stability is a vital criterion for the wood in use, especially for structural uses, as it will affect the wood performance in terms of visual and functionality. Apart from that, wood is also susceptible to a variety of deteriorating organisms, mainly Basidiomycota fungi (white rots and brown rots) and Ascomycota fungi that results in soft rot and stain. Other organisms such as termites, mold, bacteria, algae and lichens are also known to cause severe damages to wood [1]. Existence of these deteriorating agents on the wooden structure could cause financial loss and threaten users' health [2].

Treatments to reduce the hygroscopic behaviour of wood are therefore needed in order to improve its dimensional stability as well as resistance against biodeterioration agents. Thermal treatment, or heat treatment, is by far the most commercialised wood modification method. Heat treatment is typically performed at temperatures ranging from 180 °C to 260 °C, where lower temperatures did not cause any significant changes in the wood constituents while higher temperatures severely degraded the wood [3]. However, a widespread consensus has been reached among the researchers where the minimum temperature required to conduct thermal treatment on wood is 100 °C [4–6]. Nevertheless, some researchers believed that it is dependent on the wood species [7]. The effectiveness of thermal treatment on reduction in hygroscopicity of the wood was first proved by Tiemann [8], where 10–25% reduction in moisture sorption was obtained when the wood was subjected to steam at 150 °C for 4 h.

The underlying principle of thermal treatment is to convert the hydrophilic nature of wood to hydrophobic through thermal degradation of the polysaccharides, mainly thermally labile hemicellulose, in the wood cell wall [9,10]. The principle reason for the changes in wood properties is the alternations in wood chemistry as a result of exposure to high temperature [11]. Reduction in equilibrium moisture content (EMC) is the main observation in the heat treated wood as a result of thermal treatment and has been intensively studied and reported by several researchers [12–16]. Apart from that, improvement in decay resistance against biodeterioration agents such as fungi and termites is also one of the most prominent properties of heat treated wood [14–16]. Unfortunately, such improvement is usually accompanied by the decrement in mechanical strength as reported in several studies [3,17,18]. Heat treatment can be conducted in different treating media, for example, air, nitrogen and water. Each medium resulted in different extent of changes in the properties of treated wood.

Recently, heat treatment in oil has been proved to be an excellent approach to wood modification. Vegetable oils have long been used to protect woods from mold and fungi decay as well as to reduce its moisture accessibility owing to its non-toxicity and environmentally friendly nature [19]. Unsaturated oils can be oxidised when exposed to atmospheric oxygen leading to the formation of a protective layer on the surface of the wood [20]. Application of oil during heat treatment, or so-called oil heat treatment or oleothermal treatment is able to improve the properties of wood through synergetic effect of the oil and heat. Numerous studies regarding oil heat treatment of wood have been carried out by researchers around the world. However, the comparison between published literatures is difficult because the treatment procedures and parameters differ from one to another. Therefore, an integrated review on the subject is important.

A comprehensive review on wood modification by heat treatment has been done by Esteves and Pereira [21]. Reviews on thermal pretreatment methods of wood in order to produce wood composites with improved properties have been compiled by Pelaez-Smananiego et al. [22]. Several commercialised thermal modification methods on wood in Europe and its effects on the wood properties have been reviewed by Militz and Altgen [23]. Gerardin [24] reviewed different non-biocide alternatives for wood preservation where several thermal and chemical treatment methods have been discussed. Xie et al. [25] and Kocaefe et al. [26] reviewed the effects of various treatments, including heat treatment on the dimensional stability and mechanical properties of wood. Thermo-hydro (TH) and thermo-hydro-mechanical (THM) wood processes to produce environmentally friendly products and its recent development have been specifically discussed by Sanberg and Kutnar [27] and Sanberg et al. [28]. A review focused on the decay resistance of thermal treated wood has been carried out by Candelier et al. [29]. Nevertheless, to the authors' knowledge, a review on the effect of oil heat treatment on the properties of wood has yet to be done.

The objective of the present study is to conduct a systematic review of the published literature regarding the properties of wood modified by oil heat treatment and its potential uses as construction and building materials. The specific objectives of this review including: (1) discuss the pros and cons of using oil as a heating medium, (2) identify the types of different oil heat treatment and the factors that determine the effectiveness of the treatments, (3) assess the effects of oil heat treatment on the properties of wood, (4) compare the oil heat treatment with other heat treatment methods and (5) identify the potential applications of oil heat treated wood as building and construction materials.

2. Advantages and disadvantages of using oil as heating medium

Application of crude vegetable oils such as rapeseed, linseed or sunflower oil as heating medium in the heat treatment of wood can provide several advantages. Firstly, vegetable oils are good heating medium due to their ability to transfer heat to wood more readily and equally [30]. Moreover, oil can separate oxygen from wood during the treatment process and prevents the occurrence of oxidative process that leads to strength reduction in the treated samples [31]. Apart from that, the boiling points of many oils are

Table 1
Advantages and disadvantages of using oil as heating medium in oil heat treatment.

Advantage	Disadvantage
– Transfer heat within the wood more readily and evenly	– Higher tendency to burn
– Exclude oxygen during treatment process	– Higher transport costs due to oil retention in the wood
– Higher boiling points allowing higher treatment temperature	– Oil exudes from the wood over time
– Low-toxicity and environmentally friendly	– Produce undesirable odors

higher than the temperature required for the heat treatment, making it very suitable for heat treatment of wood [32]. Furthermore, additives could be added into the vegetable oils during heat treatment for wood properties enhancement purpose. Despite its relatively low-toxicity and environmentally friendly nature, heat treatment using oil as treating medium has some drawbacks. Firstly, high oil retention makes the wood heavier and increases the transportation cost. Secondly, lack of oxygen inside the wood due to the formation of protecting layer at the wood surface has limited the polymerization and oxidation process of oil. Consequently, the unpolymerized oil tends to be exuded from the wood and forming undesirable pitch-like surface. In addition, oil heat treated wood tends to emit volatile organic compounds during service which might be a source of potential secondary pollutants and undesirable odours [33,34]. Another drawback of the treatment involving oil is that the treated wood burns easily in a single-flame source test [35]. Thermally treated wood has lower fire resistance as its ignition time decreased after heat treatment [36]. The ignition time is very important in evaluating the flammability of building and construction materials. The flammability of the treated wood could have been exacerbated by the presence of oils as vegetable oils are highly flammable. Table 1 listed the advantages and disadvantages of oil application as a heating medium.

3. Different types of oil heat treatment

Thermal treatments of wood using oil that are well developed and established can be generally divided into three categories: Oil heat treatment (OHT) by Company Menz Holz in Germany, bi-oleothermal process by France's CIRAD [35,37], and Royal treatment [38].

Oil heat treatment was started by the Menz Holz company from Germany. The oil heat treatment is usually conducted at temperatures of 180 °C–260 °C using rapeseed oil, linseed oil or sunflower oil as heat transfer medium, where the oils offer excellent heat transfer characteristics and separates the oxygen from the wood. OHT process usually takes place in a closed vessel where the hot oil circulates around the wood [39]. Rapp and Sailer [40] suggested that it is necessary to maintain the desired temperature in the core of the wood for 2–4 h.

Royal process, also known as combined impregnation process, was established 37 years ago by Hager [41] as a timber drying procedure. It involves a combination of a basic impregnation with a wood preservative, followed by a treatment with hot oil [42]. Royal process is a two-step process that combines both fungicidal effect of wood preservatives and hydrophobical properties of oil [43]. Normally, two different vessels were used to perform the two-step process, namely Lowry process and oil impregnation. The typical Lowry process is a simplified method for impregnation of waterborne wood preservatives that involves a pressure phase and high vacuum at the end of the process. Meanwhile, the second step involves the treatment of impregnated wood with hot oil in a vacuum in order to hydrophobize the wood surface and subsequently inhibited the preservatives from leach [38].

Developed in France by CIRAD, bi-oleothermal process consists of two phases, hot bath and cold bath, which take place at atmospheric pressure. The wood specimens are firstly dipped in a hot oil bath with its temperature ranging from 110 °C to 200 °C, followed by dipping in an oil bath with lower temperature, usually between 20 °C and 80 °C. The first step creates an overpressure inside the wood while the second step causes water condensation and subsequently creates vacuum or depression inside the wood which allows the oil to fill the voids [35]. This depression facilitated the impregnation of liquid up to the deepest layers of wood.

Several oil heat treatment procedures that differ from the aforementioned methods were available from the literature. For example, wood was thermally modified before subjecting to oil impregnation [44]. The samples were heated in a conventional oven at 170 °C for 1 h and then soaked in an oil bath at room temperature for 2 h. Awoyemi et al. [45] used in-treatment cooling where the samples were immersed in a hot oil bath at 220 °C. After immersion for 2 h, the samples were left to soaked and cooled in the oil bath and it was only removed when the desired temperature is reached. Dubey et al. [46] applied post-treatment cooling after oil heat treatment where the samples in hot bath were removed after ½, 1, 1½, 2, 4, 8 and 12 h of cooling in the oil bath.

4. Factors that influence the effectiveness of oil heat treatment

The type of heating medium, period of heating, peak temperature and wood species are the most important parameters of thermal modification processes [47]. Although application of oil and thermal treatment together are able to improve the properties of wood through synergetic effect, they are, however, essentially different in terms of function. Oil absorbed by wood is the influential factor in improvement of water absorption while thermal treatment is mainly responsible for reducing the hygroscopicity and thickness swelling of the treated wood. Therefore, the efficiency of the oil heat treatment is very much dependent on several factors such as oil types, thermal treatment conditions, and oil retention in the wood [48].

4.1. Oil type

It is well known that the thermal conditions, such as treatment temperature and time, exert significant effect on the properties of the treated wood. Apart from that, the efficiency of the oil heat treatment is dependent on the type of oil that is used as a heating medium. Wang and Cooper [48] found that palm oil is more effective than soybean oil in improving the dimensional stability of oil heat treated white spruce. Lyon et al. [49], on the other hand, found that the drying properties of the vegetable oils play a vital role on the extent of improvement of treated wood in resistance against decay. The authors reported that, among the three vegetable oils studied, linseed oil is the most effective oil to produce durable samples followed by soybean and rapeseed oil. This phenomenon can be attributed to the fact that linseed oil is a drying oil with high content of polyunsaturated fatty acids such as linolenic acid and linoleic acid or monounsaturated acid such as oleic acid. Therefore, owing to its high unsaturation degree, linseed oil effectively restricted the penetration of water into the wood samples. The average fatty acid composition (wt%) of selected oils commonly used in heat treatment are presented in Table 2. The drying characteristic of the vegetable oils is decided by its degree of unsaturation degree and can be determined by iodine values. Oils with high iodine values are drying oil and otherwise. Oils with higher iodine values oxidize and polymerize faster and form an elastic film on the wood surface when exposed to air [50]. Chemical reactions of vegetable oils with wood are based on the auto-oxidation of

Table 2
Average fatty acid composition (wt %) of selected oils commonly used in heat treatment [52].

Fatty acids	Lipid number	Linseed	Soybean	Canola/Rapeseed	Cottonseed	Sunflower	Peanut	Palm	Coconut	Corn
Caproic	6:0	–	–	–	–	–	–	–	0.4	–
Caprylic	8:0	–	–	–	–	–	–	–	7.3	–
Capric	10:0	–	–	–	–	–	–	–	6.6	–
Lauric	12:0	–	–	–	–	0.5	–	0.2	47.8	–
Myristic	14:0	–	0.1	–	0.9	0.2	0.1	1.1	18.1	–
Palmitic	16:0	6.0	11.0	3.9	24.7	6.8	11.6	44.1	8.9	10.9
Palmitoleic	16:1	0.1	0.1	0.2	0.7	0.1	0.2	0.2	–	–
Stearic	18:0	2.5	4.0	1.9	2.3	4.7	3.1	4.4	2.7	1.8
Oleic	18:1	19.0	23.4	64.1	17.6	18.6	46.5	39.2	6.4	24.2
Linoleic	18:2	24.1	53.2	18.7	53.3	68.2	31.4	10.1	1.6	58.0
Linolenic	18:3	47.4	7.8	9.2	0.3	0.5	–	0.4	–	0.7
Arachidic	20:0	0.5	0.3	0.6	0.1	0.4	1.5	0.4	0.1	–
Gadoleic	20:1	–	–	1.0	–	–	1.4	–	–	–
Eicosadienoic	20:2	–	–	–	–	–	0.1	–	–	–
Behenic	22:0	–	0.1	0.2	–	–	3.0	–	–	–
Lignoceric	24:0	–	–	0.2	–	–	1.0	–	–	–

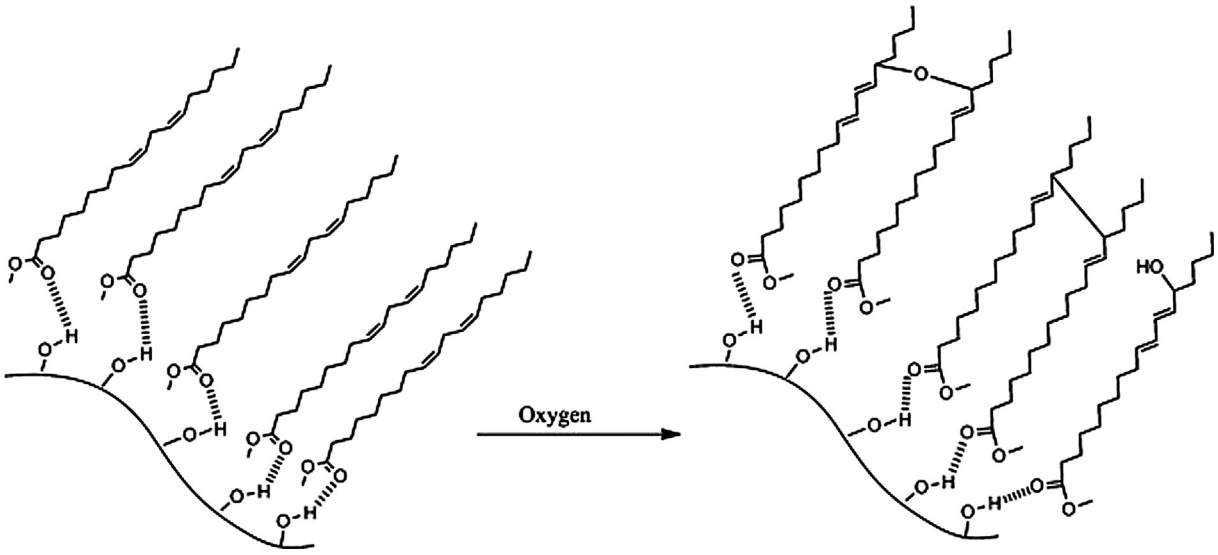

Fig. 1. Hydrogen bonds forming between hydroxyl groups of wood surface with ester functional groups [53, with permission].

unsaturated fatty acids and their derivatives which involves a series of reactions such as initial, oxidation, rearrangements, and coupling or scission reactions [51]. Wood carbohydrates possess very high amount of immobile hydroxyl groups. These hydroxyls on the wood surface will react with the ester functional groups present in vegetable oils to form strong hydrogen bonds and holding them in a position suitable for reaction as shown in Fig. 1.

The age of the oil used in heat treatment also significantly affected the efficiency of the treatment. Dubey et al. [31] observed that the water absorption of wood treated in oil pre-heated at 180 °C for 6–27 h was higher than that of treated in fresh oil. Higher viscosity of the pre-heated oil due to the evaporation of volatile compounds and heat polymerization has limited oil uptake in the wood and resulted in poorer protection against moisture. However, it is interesting to note that the volumetric swelling did not show significant different among pre-heated oil and fresh oil, further proving the statement that oil uptake is a more influential factor in improving the water absorption of the wood.

4.2. Treatment parameter and procedure

In general, treatment temperature and time are the most critical elements in deciding the extent of effectiveness for oil heat treatment as the swelling and strength reduces as a result of increasing treatment temperature and time. Dubey et al. [31] reported that the treatment temperature is the more crucial parameter compared to treatment time as no significant difference was detected between specimens treated for 3 h and 6 h at the same level of temperature. Apart from that, treatment procedure applied also plays an important role. The rate of oil consumption is dependent on the treatment procedure. Octavia et al. [54] compared three treatment procedures: (i) hot bath at 95 °C for 30 min followed by cool bath at 30 °C for 30 min, (ii) hot bath at 95 °C for 1 h and (iii) cold bath at 30 °C for 1 h. The results revealed that the samples treated using the first treatment procedure had the highest oil consumption and mass increase. Dissimilar to the high heat temperature and long heating time that was employed by Dubey et al. [31], at milder temperature and relatively shorter heating time, the oil is less viscous and penetration into cell wall is easier. Consequently, in the cold bath stage, the oil absorption was facilitated by the partial vacuum created.

Awoyemi et al. [45] treated ponderosa pine and Canadian black spruce using in-treatment cooling approach where the samples were soaked in soy oil at 220 °C for 2 h. After 2 h, some samples were removed immediately while some samples were removed when the oil temperature cooled down to 180 °C and 135 °C, respectively. Higher oil uptake was recorded in the samples removed after cooling process. The oil uptake of the samples that

was removed at 180 °C (50 min cooling time) was 30% and the oil only penetrated the outer layer of 5 mm of the wood. However, higher oil uptake throughout the sample thickness (approximately 80% on the surface and 50% in the inner zones) was recorded in the samples that removed at 135 °C (2 h cooling time). The cooling process causes the air in the wood's void space to contract, creating a vacuum to promote oil penetration into the wood. Grenier et al. [55] identified two mechanisms of oil impregnation into the wood during heat treatment. The first mechanism is the spontaneous absorption by the wood itself when the wood has stronger affinity to oil than to water. The second mechanism is when the capillary forces between the oil and the wood are greater than water vapour that is moving out of the wood in the opposite direction. Due to this pressure gradient, limited amount of oil is able to penetrate into the wood during oil heat treatment but most of the oil infiltrates the wood at the end of treatment and during the cooling phase.

4.3. Wood anatomy

High retention of oil is necessary to offer long-term protection to the treated wood. Zlahtic et al. [56] treated chestnut heartwood, European larch heartwood, Scots pine heartwood and sapwood, and Norway spruce wood with tung oil and linseed oil using vacuum-pressure impregnation and immersing methods. The obtained results confirmed that the oil uptake is strongly dependent on wood permeability. Tomak et al. [50] observed that, due to different permeability, oil retention in Scots pine is higher than beech wood, which is 550 kg/m^3 and 390 kg/m^3, respectively. As reported by Tomak et al. [50], beech (*Fagus orientalis*) samples treated at 160 °C for 30 min with lower oil retention were reported to have higher water absorption compared to Scots pine (*Pinus sylvestris*) samples. Wood cross section is also one of the factors that decide the extent of improvement in dimensional stability. Wang and Cooper [48] reported in their study that the treatment seemed to be more efficient in improving the radial than the tangential dimensional stability. However, this finding was not compatible with Tjeerdsma et al. [57] who produced contradicting results.

Hardwood is more affected by thermal treatment compared to softwood. Hardwood carbohydrates (xylan) are less thermally stable compared to softwood carbohydrates (galactoglucomannans) and consequently decompose when subjected to milder temperature. In addition to that, higher amount of acetyl groups presents in hardwoods release more acetic acid during heat treatment that catalyses acid hydrolysis and consequently results in higher weight loss compared to softwoods [58]. Oumarou et al. [59] reported that the impact of heat treatment is directly proportionate to the specific gravity of the wood. Wood with higher specific gravity, or denser wood, has lower temperature during thermal treatment and requires higher energy to heat due to its lower diffusivity. Owing to lower thermal diffusion, the heat transfer rate is slower from the wood surface to the centre of the wood and therefore the moisture removal rate is also correspondingly slow. Gao et al. [60] treated 2 softwoods species (spruce and fir) and 2 hardwoods species (beech and ash) using Termovuoto process (vacuum drying followed by thermo-treatment) and reported that the resistance against white and brown rot fungi differed between softwood and hardwood, where the hardwood exhibited higher mass loss than softwood. Ferrari et al. [61] also claimed that, in their study, mass loss of spruce and fir were lower than that of beech and ash. These results are consistent to patterns of weight loss data in the literature. Ferrari et al. [61] reported that weight loss of ash and beech is higher than that of spruce and fir at treatment temperatures of 200–220 °C during the Termovuoto process. Hardwoods contain in general more polysaccharides, particularly hemicelluloses, and less lignin than softwoods and thus the weight loss of the former are higher due to thermal degradation of hemicelluloses. Therefore, the temperature effects in case of hardwoods are more pronounced than that in case of softwoods.

5. Effect of oil heat treatment on the properties of wood

5.1. Colour changes

The colour of natural wood is decided by the chromophores that exist in the lignin and extractives. Degradation of hemicelluloses during heat treatment produced some additional chromophores to the wood and lead to changes in colour [62]. Darkening of wood after heat treatment is a common observation where the extent of darkening is a function of increasing temperature. Apart from the treatment temperature, the extent of oil uptake also affects the wood colour change. Wood that absorbed more oil tends to be darker in colour [63]. As illustrates in Fig. 2, the darkness of wood colour increased proportionally with the increase of the temperature. Darkening of wood colour during heat treatment is caused by formation of degradation products from hemicelluloses, changes in extractives, and the formation of oxidation products such as quinones [64]. Sundqvist [65] also stated that the production of chromospheres as a result of the hydrolytic reaction that occurs during heat treatment also contributes to colour changes in heat-treated wood. However, in the oxygen-excluded treating medium like oil, formation of an oil layer on the wood surface as a result of heat treatment and caramelisation of soluble sugars is a more probable explanation to the darkening effect. Toker et al. [66] suggested that the caramelisation of soluble sugars produced from hydrolyzed hemicellulose during heat treatment gave a darker colour to the wood.

Dubey et al. [31] treated Radiata pine wood in linseed oil at 180 °C for 3 h and revealed that the colour variation between treated and untreated wood is great where the lightness reduced significantly and the reddish and the yellowness increased. Treated using bi-oleothermal process (160 °C/0.5 h followed by room temperature/0.5 h), the wood turned almost black with formation of char clearly visible on the surface of wood [67]. Nemeth et al. [62] reported that the extent of darkening is highly dependent on the extractive content of the wood. The effect of addition darkening effect due to oxidation process is more pronounced in the wood with higher extractive content. Razak et al. [68] revealed that the extent of changes in colour varied between sapwood and heartwood. Sapwood of Acacia hybrid treated in hot palm oil showed

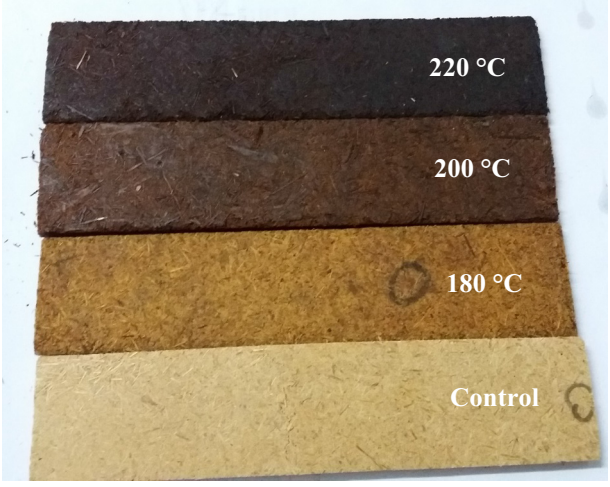

Fig. 2. Changes in colour of the oil heat treated particleboard at different treatment temperatures.

tremendous decrease in lightness in comparison to heartwood, mainly due to its brighter colour. Oil heat treatment bestowed the wood with better colour stability after weathering. Dubey et al. [69] revealed that untreated Pinus radiata wood had greater colour variation after accelerated UV weathering test compared to oil heat treated wood, where the colour stability increased with treatment temperature. Bak et al. [70] treated pannonia poplar in sunflower oil and found that the wood treated at the highest temperature and longest duration underwent the least total colour changes after 1-year exposure. Treated in sunflower oil, black locust and poplar wood exposed to short-term UV radiation exhibited better photostability compared to untreated samples [62]. Apart from a more stable colour, oil heat treatment was also found to be able to prevent cracking, warping or twisting of the treated wood [69]. Berard et al. [71] observed that the chestnut tree exhibited significant reduction in peripheral and end crack when treated in rapeseed oil bath at 130 °C for 1 h.

5.2. Dimensional stability

Oil heat treatment resulted in reduction of equilibrium moisture content (EMC) in the treated samples and, correspondingly, reduced its water absorption which consequently leads to better dimensional stability. The reduction in EMC can be caused by several heat-induced factors such as diminishing amount of the water affinity hydroxyl groups [72]; inaccessibility of hydroxyl groups to water molecules due to increment of cellulose crystallinity [73,74]; and further crosslinking caused by the polycondensation reactions in lignin [11,75]. In the oil heat treatment, oil uptake, deposit of oil in the cell wall and formation of protective layer on the wood are also the main factors that contribute to the improvement in dimensional stability of the wood.

Dubey et al. [76] treated *Pinus radiata* wood using linseed oil at temperature of 160 °C, 180 °C and 210 °C for 1 h, 3 h, and 6 h, respectively. The treated wood showed improvement in volumetric swelling percentage (S) and anti-swelling efficiency (ASE) compared to untreated wood. The highest ASE of 53–60% was found in specimens treated at the highest temperature. Wang & Cooper [48] treated white spruce (*Picea glauca*) using commercial palm oil, soy oil and slack wax at 200 °C and 220 °C for 2 and 4 h, respectively, and revealed that a MEE of 30–52% were recorded after the oil heat treatment. Awoyemi et al. [45] treated ponderosa pine and black spruce using in-treatment cooling method where the samples were removed at the desired temperatures when the treatment is completed. The results revealed that the wettability of the treated samples was greatly reduced as increased contact angle and surface energy were recorded. The rate and the amount of water absorption and thickness swelling of wood reduced as the cooling time increased.

Fang et al. [77] found that the oil heat treatment has eliminated the compression set recovery of the densified aspen wood veneers and subsequently lead to better dimensional stability. Compression set recovery, also called as shape memory, is a phenomenon where the compressed wood returns to its original shape without the influence of external force after being subjected to heat and moisture [28]. In order to prevent the compression set recovery of densified wood due to high humidity level, Norimoto et al. [78] suggested three mechanisms. The first mechanism is to form cross-linkages between molecules of the matrix constituents to prevent the relative displacement of microfibrils. Second, to relax the stress stored in the mcrofibrils and matrix. Third, to isolate the hydrophilic cell wall constituents from the reach of moisture. The function of the oil heat treatment is focused on the second and third mechanisms. Welzbacher et al. [79] treated thermo-mechanical densified Norway spruce in heated rapeseed oil in an experimental treatment vessel at BFH in accordance with the procedure described by Sailer et al. [63]. With the increasing oil heat treatment in temperature and duration, the swelling decreased significantly. The prolongation of densification duration as well as the elevation of densification temperature caused a slight reduction of maximum swelling. Densification at 200 °C for 4 h without post-treatment reduced the swelling to 34%, analogical to the effect of an oil-heat treatment at 200 °C for 4 h independent from the densification parameters. Study by Mirzaei et al. [80] also reported that thermal treatment reduced the moisture induced stresses that occur when the glulam was exposed to the changes of moisture and subsequently resulted in shape distortions and, during re-drying process, led to cracks on the surface. Therefore, glulam made from the thermally treated poplar wood had lower moisture induced stresses owing to its reduced hygroscopicity and showed better bending strength and stiffness.

In comparison to the extensively studied temperate wood species, the study of oil heat treatment on tropical wood species is relatively scarce. Jalaludin et al. [81] study in thermally modified *Acacia mangium*, a major plantation species in the humid tropical lowlands of Asia, and sesenduk (*Endospermum malaccense*) wood in heated palm oil and its water vapour sorption isotherms was reported. According to the study, oil heat treatment was found to have decreased the fiber saturation point (FSP) of the treated wood as a function of treatment temperature. Nevertheless, the treatment temperature exerted greater influence to the reduction of polylayer water while the monolayer water of the treated wood was less temperature dependent. 54.6% and 56.8% reduction in FSP was recorded for *Acacia mangium* and sesenduk wood treated at 220 °C. The differences in adsorption/desorption behaviour between oil heat treated and untreated was noticed when the oil heat treated wood exhibited a marked reduction in EMC. However, sesenduk wood is more affected by the treatment compared to that of *Acacia mangium*, probably due to its lower quantity of extractives [82].

Apart from vegetable oils, Okon et al. [83] used silicone oil as heating medium to treat Chinese fir wood. Different extent of shrinkage reduction was recorded in the tangential, radial and longitudinal directions after the treatment. The decrement in shrinkage values for tangential direction is higher than radial and longitudinal directions. Barnett and Bonham [84] attributed this phenomenon to the vertical orientation of micro fibrils in the S2 layer of the cell wall. As the tangential direction possess micro fibrils with greater angle, it displayed higher reduction in shrinkage compared to the other two directions. Similarly, the highest anti-swelling efficiency (ASE) was recorded in tangential direction, followed by longitudinal and then radial directions. A hydrophobic surface resulted from the treatment of Chinese parasol wood in silicone oil where higher contact angle of 136.1° was observed in comparison to 53.9° in untreated wood [85].

5.3. Mechanical properties

Strength properties of the wood are affected after oil heat treatment due to heat-induced alteration of wood chemical structure of cell wall components. The three main cell wall components, hemicellulose, cellulose and lignin contribute differently to the strength properties of the wood. Homan and Jorissen [86] referred these cell wall components metaphorically as concrete, where hemicellulose is cement that functioned as bonding agent, cellulose is reinforcement that contributes to the tension forces and lignin is sand or small stones responsible for compression forces. Consequently, alteration on any of these components will result in different extent of changes in strength properties.

In oil heat treatment, oxygen-free atmosphere is not the only reason that results in relatively good mechanical properties of wood. High oil uptake, on the other hand, also contributes to better

mechanical strength of the wood compared to the other heat treatment methods. Tomak et al. [67] found that the compression strength parallel to the grain (CSPG) of the oil heat treated Scots pine and beech wood did not show significant reduction. In fact, some of the treated samples even showed higher CSPG compared to that of the control samples as higher density was recorded in the treated wood due to high oil retention. It is believed that oil might fill the lumen and thickens the cell wall and bestows better lateral stability to the wood which normally fails in compression as a result of buckling of relatively thin cell walls. Similar findings were also reported by Cheng et al. [30] where CSPG for poplar wood increased after oil heat treatment, mainly due to the high oil uptake that thickened the fibers and enhanced their lengthwise strength. Bak & Nemeth [87] treated Poplar (*Populus* × *euramericana* Pannónia) and Robinia (*Robinia pseudoacacia* L.) wood in sunflower, linseed and rapeseed oils at 160 °C and 200 °C for 2 h, 4 h and 6 h, respectively. Interestingly, oil heat treated poplar wood exhibited increment in compression strength by 15–25%. On the other hand, compression strength of Robinia wood increased by 5–15% when treated at 160 °C but started to decrease by 5–10% when treated at 200 °C. Windeisen et al. [88] attributed the findings to the increase in lignin condensation during heat treatment. Lower amount of bound water in heat treated wood, increment of crystalline cellulose as well as limited movement perpendicular to the grain due to increased cross linking of lignin polymer network are also some probable explanations to the improvement in compression strength [89].

Increment in MOE of poplar was observed when subjected to temperature of 160 °C. However, it decreases when the treatment temperature and time increased [90]. The slight increase in MOE under milder treatment temperature can be explained by degradation of amorphous cellulose content and increase in the relative crystallinity [91]. In addition, transformation of the wood amorphous polymeric materials from glassy state to rubbery or plastic state at the glass-transition temperature might increase the MOE of the heat treated samples [92]. Megnis et al. [93] revealed the hydraulic effects of oil present in the cavities might have contributed to the slightly increment in flexural modulus. Fang et al. [94] treated densified aspen wood veneers in canola oil at 180 °C, 200 °C and 220 °C for 1 h, 2 h and 3 h, respectively. Although better mechanical strength due to the densification effect was still prevalent compared to non-densified control wood veneers, oil heat treatment clearly reduced the Brinell hardness, tensile strength and modulus of rupture of the densified wood veneers. However, no significant change in tensile MOE was observed and the bending MOE increased after oil heat treatment.

5.4. Durability against biodeterioration agents

Improvement in decay resistance against biodeterioration agents such as fungi and termites are one of the most prominent property of heat treated wood, apart from dimensional stability. Kamdem et al. [14] and Weiland and Guyonnet [95] classified the reasons for the improvement in durability of wood by heat treatment against fungal attack into four categories, namely, (1) enhancement in hydrophobic character of wood, (2) production of extractives, (3) modification of the wood polymers and (4) degradation of hemicelluloses. Improvement in resistance against fungal decay has been proven by a number of researchers based on the underlying principle that the heat-treated samples exhibit hydrophobic features, where the growth of fungi was inhibited due to the low content of moisture [49,96,97]. Li et al. [98] established an equation to predict the durability of heat treated poplar wood against soft-rot fungi based on the hygroscopicity of the wood. As a result, hygroscopicity of the wood correlated well with the durability against soft-rot fungi and this method showed a promising future to substitute the conventional and time-consuming evaluation method.

Oil heat treatment has been proven to be a very effective method in enhancing the resistance of wood against fungus. The effects of oil heat treatments on the termite and fungal decay resistance of wood are summarised in Table 3. Sailer et al. [63] treated spruce and Scots pine in vegetable oil baths with temperatures of 180 °C, 200 °C and 220 °C. Apart from having more consistent appearance and lower mechanical strength loss, wood treated in hot oil exhibited better resistance against *Coniophora puteana* in comparison to the wood treated in air atmosphere at the same temperature levels. Spruce and fir wood subjected to oil heat treatment at 200 °C and 220 °C for 2 h and 4 h exhibited better resistance against *Gloeophyllum trabeum* and mold. Wood that classified as "Resistant" with mass loss below 20% was achieved when treated in soybean oil at 220 °C for 4 h [99]. Oil heat treatment, together with PLATO process, was found to be able to produce durable wood according to EN 350-1 [100], while Thermowood and Ratification process were able to produce wood that was "moderately durable" [101]. Tensile strength loss caused by the soft rot fungus *Chaetomium globosum*, in pine wood treated in linseed oil at 200 °C for 30 min was less severe compared to that of untreated samples [102]. Spear et al. [103] compared the resistance of Corsican pine and Norway spruce against brown rot fungi, *Coniophora puteana* and *Postia placenta*, after immersion in hot linseed oil, rapeseed oil and a proprietary resin derived from linseed oil at temperatures of 180 °C and 200 °C. The results revealed that the resistance of wood treated in non-drying rapeseed oil showed higher mass loss compared to that of the wood treated in drying linseed oil and therm-oxidatively cured resin. Tomak et al. [67] revealed that the efficiency in wood protection against fungal attack is highly dependent on the type of oil used as heating medium. The researchers concluded that waste and sunflower oil offered the best protection against fungal decay in comparison to other vegetable oils such as nut, soybean, canola and corn oil. The efficiency of the vegetable oils might be related to chemical composition of oils, their drying properties and the barrier properties of the dry film. Apart from wood, oil heat treatment also proved to have enhanced the durability of bamboo against *Coriolus versicolor* when subjected to heat treatment in palm oil at various temperature levels [104].

However, this assumption is not completely applicable for termite resistance as numerous studies revealed that heavier attacks in the heat-treated samples compared to that of the untreated samples [105,106]. Surini et al. [106] suggested that the toxic components produced during heat treatment of wood were the main reason that caused the mortality of termites. However, the toxicity was not efficient in short-term and therefore it did not completely prevent the treated wood from being eaten by termites. Moreover, reports on termite resistance in oil heat-treated woody materials are scarce. Smith et al. [107] reported that oil heat treatment using rapeseed oil solely was not sufficient to enhance the termite resistance of the treated Scots pine and Norway spruce. Instead, oil heat-treated samples exhibited higher weight loss caused by termites when compared to the control samples. On the contrary, Manola and Garcia [108] observed a significant improvement in terms of termite resistance in bamboo (*Dendrocalamus asper*) treated with hot coconut oil. Lyon et al. [49] treated Japanese cedar and beech with hot vegetable oils (linseed, soybean, and rapeseed) and found that the weight loss of the samples due to termites' attack was reduced.

Significant improvement in termite resistance of thermal treated *Grevillea robusta* heartwood has been reported by Mburu et al. [109]. However, the resulted resistance is mainly due to the termiticide extractives contained in tropical heartwood [106]. Many studies revealed that heavier attacks by termites were

Table 3
Effects of oil heat treatments on the termite and fungal decay resistance of wood.

Wood species	Oil type	Treatment conditions	Termites/Fungi	Findings	Reference
Termites					
Scots pine (*Pinus sylvestris* L.) Norway spruce (*Picea abies* L.)	rapeseed	220 °C for 4 h	*Coptotermes farmosanus* Shiraki	Weight loss of treated samples (50.04 and 55.26%) was higher than control (40.30 and 53.93%)	[107]
Scots pine (*Pinus sylvestris* L.)	rapeseed	Impregnation with hot oil at 120 °C + 120 °C hot air for 24 h	*Coptotermes farmosanus* Shiraki	3.76% weight loss compared to control (40.30%)	[107]
Japanese cedar (*Cryptomeria japonica* D. Don) Beech (*Fagus crenata* Blume)	rapeseed soybean linseed	double dipping of one hour each: first in a hot bath at 130 °C and second in a cold bath at 80 °C	*Coptotermes formosanus* Shiraki	Weight loss caused by termite were reduced in half	[49]
Dendrocalamus asper	coconut	Heat treated at 140, 160, 180 and 200 °C for 30, 60 and 120 min	*Microcerotermes losbañosensis*	Average mass loss of 34.09–56.74% in treated samples compared to control (79.73%)	[108]
Fungi					
Red pine (*Pinus resinosa*)	soy	Pre-freezing at -20 °C before treated in oil at 220 °C for 2 h and 4 h	*Amitermes evuncifer*	Frozen wood showed lower mass loss after oil heat treatment compared to untreated wood	[120]
Pine (*Pinus sylvestris*) Spruce (*Picea abies*)	linseed oil	180 °C, 200 °C and 220 °C for 4.5 h	*Coniophora puteana*	Pine control (40%) Spruce control (48%) Weight loss <2% at 200 C for pine and 220 C for spruce	[40]
Alder (*Alnus glutinosa*, L.)	vegetable oil	180 °C for 6 and 10 h	*Trametes versicolor*	38.4% and 56.2% better than control	[121]
Aspen (*Populus tremula* L.)	linseed oil	190, 205 and 220 °C for 4.5 and 6 h	*Coriolus versicolor* *Coniophora puteana*	58.32–70.90% 57.76–77.87%	[122]
Alder (*Alnus glutinosa* L.)	soy oil	180 and 200 °C for 6 and 10 h	*Trametes versicolor* *Postia placenta*	10–20% versus control (>25%)	[47]
Japanese cedar (*Cryptomeria japonica* D. Don) Beech (*Fagus crenata* Blume)	rapeseed soybean linseed	double dipping of one hour each: first in a hot bath at 130 °C and second in a cold bath at 80 °C	*Fomitopsis palustris* *Trametes versicolor*		[49]
Scots pine (*Pinus sylvestris*) Beech (*Fagus orientalis*).	nut sunflower soybean canola corn waste vegetables oil	Impregnation with boron compounds, then heated in oil bath at for 160 °C for 30 min before immersed in oil bath at room temperature for another 30 min	*Coniophora puteana* for Scots pine *Coriolus versicolor* for beech	Beech: Control – 50.72–55.90% Oil only – 7.08–12.90% Oil + boron – 0.82–1.83% Pine: Control - 28.70–37.71% Oil only – 7.28–14.19% Oil + boron – 0.36–1.34%	[67]
European ash (*Fraxinus excelsior*) European aspen (*Populus tremula*) European beech (*Fagus sylvatica*) European birch (*Betula pubescens*) European larch (*Larix decidua*) European oak (*Quercus robur*) Scots pine (*Pinus sylvestris*) Norway spruce (*Picea abies*)	rapeseed linseed linseed tung	200 °C for 1 h followed by immersed in oil bath at room temperature for 1 h	*Coniophora puteana*	Control – 35.6–52.3% Rapeseed – 3.8–23.8% Tung – 0.7–22% Linseed – 0.6–10.4%	[123]
Rubberwood (*Hevea brasiliensis*)	palm	Heat treated at 172–228 °C for 95–265 min	*Pycnoporus sanguineus*	Decay resistance of treated rubberwood against white rot fungi improved with increased treatment temperature and time	[32]
Pinus radiata	linseed	Immersed in oil at 160, 180 and 210 °C for 1 h, 3 h and 6 h	*Oilgoporus placenta*	Control – 19.2% Treated – 13.2–17.6%	[76]
Acacia hybrid	palm	Immersed in oil at 180, 200 and 220 °C for 30, 60 and 90 min.	*Coriolus versicolors* *Gloeophyllum trabeum* *Pycnoporus sanguineus*	Control - 31.42%Treated - 3.26 – 12.55% Control – 26.59% Treated – 9.41–12.55% Control – 20.89% Treated – 0.88–4.07%	[124]

observed in the thermal treated wood compared to that of the untreated wood [105,106,110]. As cellulose and hemicelluloses are degraded in heat treatment, heat treated wood would be easily digested by termites [111]. Unfortunately, studies on durability of oil heat-treated wood against termites are relatively scarce in comparison to the other thermal treatment methods and contradicting findings were reported. Smith et al. [107] and Nunes et al. [112] reported that oil heat treated wood did not show any toxicity

and repellent characteristics toward termite. However, better durability could be achieved provided that the oil retention after treatment is high [109]. Contrarily, Lyon et al. [49] observed an improvement in termite resistance when Japanese cedar and beech were subjected to heat treatment in vegetable oils. Manola and Garcia [108] also reported positive results when bamboos were treated with hot coconut oil. These ambiguous results might be due to either toxic compounds or feeding stimulants for termites which were formed by the degradation of wood extractives [113,114].

Timber species that possess higher extractive content and density displayed superior durability. Kadir and Hale [115] compared the resistance of twelve Malaysian timber species against subterranean termites and observed that the durability of the timbers varied according to their extractive content and density. Digestions of lignocellulose by termites were interfered by the antioxidants substances contained in wood extractives and, consequently, the termites have learnt to avoid wood that possesses a certain amount of the antioxidant compounds [116]. Removal of these extractives during thermal treatment might have caused some adverse effects on its ability to resist termite since extractive is well-known to have imparted better insect and decay resistance to the wood [117]. Volatile extractives, for example terpenes, can evaporate during the first stage of heat treatment [118]. Attractive substances might have been produced during thermal treatment of wood and become the feeding attractants or stimulants for the termites [119]. Low molecular sugar products are created owing to the degradation of the polysaccharides and can be easily eaten by termites and caused more mass loss to the treated wood [105].

6. Comparison between OHT and other heat treatment methods

Several authors have compared the efficiency between thermal treatment methods in terms of some selected properties. Generally, oil heat treated wood provided better dimensional stability in comparison to wood treated in hot air. Beech wood treated in hot sunflower oil exhibited statistically better dimensional stability, equilibrium moisture content, fiber saturation point, and moisture content compared to that of treated in hot air [125]. Yang et al. [126] compared the properties of the moso bamboo heat-treated in different heating media, namely air, nitrogen and linseed oil. The results suggested that heat treatment in linseed oil is the most effective method in improving the dimensional stability of the moso bamboo, even at lower temperatures.

Epmeier et al. [127] compared OHT of Scots pine, beech and birch wood with other modification method such as acetylation, impregnation with methylated melamine formaldehyde, furfurylation, maleoylation and succinylation. The findings revealed that OHT led to only a small reduction in EMC in comparison with acetylation. Gobbaken and Westin [128] exposed modified Scots pines outdoor for 3.5 years and found that oil heat treated Scots pine performed better than acetylated and heat-treated samples as a lower degree of mold growth were detected. Among all of the modified wood samples, furfurylated samples had the lowest degree of mold growth after 3.5 years of outdoor exposure. Palanti et al. [129] impregnated a mixture of mineral and vegetable oils containing 0.15% propiconazole and 0.15% tebuconazole heated at 80 °C into Stone pine and Scots pine wood followed by natural durability test in the field. The results revealed that, after 5 years of exposure in the field, wood samples treated in hot oil showed better performance in comparison with that of the samples treated in wax impregnation and thermal treatment using ratification process. The lowest decay grade was found in the heated-oil treated samples. Westin et al. [130] compared the efficiency between 12 wood modification methods against marine borer attack. The results revealed that oil heat treatment of Scots pine using rapeseed oil resulted in far more inferior resistance compared to furfurylation and methylated melamine resin treatment.

7. Potential applications of oil heat treated wood

Thermally treated wood is usually recommended for non-structural applications as reduced strength is one of the main criteria resulted by the treatment. However, thermally treated wood possesses enhanced moisture resistance and dimensional stability as well as dark brown colour that are well suited for floorings [131,132]. In addition to its improved biological durability and weather resistance, wood treated in hot oil could be used for exterior applications such as fencing, garden furniture and cladding. As for floorings, oil heat treated wood exhibited superior colour stability, dimensional stability, scratch and abrasion resistance that are suitable for the mentioned usage. Nejad et al. [132] treated maple and hemlock wood in soybean oil at 180 °C and then coated with water-based wood flooring coating systems. The coated samples were tested with house-hold chemicals such as vinegar, mustard, ketchup, vegetable oil, coffee, acetone, ethanol and sodium hydroxide. The results revealed that, while maintaining acceptable coating adhesion, the coated oil heat treated wood has better colour retention, scratch resistance and abrasion compared to that of the coated untreated wood.

Besides floorings, oil heat treated wood is also suitable for outdoor applications such as cladding, garden furniture, decks, fencing and external joinery [133]. Studies have shown that oil heat treated wood exhibited superior durability against mold and fungal decay after being exposed in outdoor for 3–5 years [129,130]. Therefore, it is very suitable for outdoor above ground applications. However, coatings on the oil heat treated are always recommended for exterior applications as it is very effective against weathering [134]. As the oil heat treatment reduced the wettability of the wood surface, selection of appropriate coating systems is vital to ensure an acceptable adhesion between the coating and the hydrophobic wood surface. Rapp and Sailer [40] reported that oil heat treated pine and spruce possesses better paintability for acrylic water based paints and alkyd solvent based system compared to that of the wood treated in hot air.

The presence of oils on the surface could adversely affect the adhesion of coatings. Therefore, some treatments are needed [135]. Sanding could improve the adhesion of the coatings by increasing its wettability [136]. Good gluability was also observed in oil heat treated wood after planing [40]. Apart from sanding, some other treatments could be done on the surface of the treated wood to enhance the coating performance. Sam Williams et al. [137] treated the oil heat treated wood surface with sol–gel alumina and found that the treatment was in favour to the waterborne Polycrylic finish while the adhesion of solvent-borne polyurethane finishes was significantly degraded. Plasma treatment is another treatment that aims to remove the oil from the treated wood surface and successively improve its wettability [138]. As a result, adhesion of the coatings was improved. Nonetheless, oil heat treatment is not entirely detrimental to the adhesion of coatings. In a study done by Petric et al. [139], the wettability of oil heat treated Scots pine wood was measured using commercial exterior waterborne systems. In their study, even though the hydrophobic character of treated wood increased, the exterior waterborne coatings exhibited much better wetting properties on oil heat treated wood. This finding opens up the possibilities for application of environmentally friendly waterborne surface systems on modified wood for outdoor applications.

8. Conclusions

Oil heat treatment of wood has been extensively studied and recognized as an efficient and environmentally friendly method to improve selected properties of wood. This paper reviewed the application of vegetable oils as heating medium for the modification of wood. Different treatment procedures were outlined and its effects on the physical, mechanical and biological properties of the wood were reported. The following summaries can be drawn based on the review of the present literatures and works:

1. Oil is a good heating medium that transfer heat readily and evenly into the wood samples and excluded the wood from the exposure of oxygen during the treatment.
2. There are several types of oil heat treatment where 3 of them are well developed and established, namely oil heat treatment by the Menz Holz company of Germany, Royal treatment and bi-oleothermal treatment.
3. The effectiveness of the treatment is highly dependent on the type of oil used, treatment procedures and wood anatomy. Drying oil is preferable as it oxidised and polymerized faster and form an elastic film on the wood surface to prevent water uptake. Treatment method that allows cooling phase in the oil bath is recommended as the penetration of oils happens readily during cooling. Wood with higher permeability tends to exhibits better results.
4. Generally, oil heat treatment causes darkening in the wood and better photostability compared to untreated wood. Polysaccharides are the most affected wood constituents while lignin remained relatively resistant to high temperature. As a result, better dimensional stability is attained. Relatively better mechanical strength was observed due to the oxygen-free treatment condition and high oil uptake. Resistance against fungi had improved significantly while resistance against termites had some controversial findings among the published works.
5. In comparison to other wood modification methods, wood treated in oil exhibited superior dimensional stability compared to samples treated in hot air and nitrogen.
6. Oil heat treated wood is suitable for floorings and outdoor applications such as fencing, garden furniture and cladding due to its enhanced moisture resistance and dimensional stability as well as biological durability.

Conflict of interest

The authors declare no conflict of interests regarding the publication of this paper.

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