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Emission of Volatile Organic Compounds from the Heat Treatment of Afrormosia and Newtonia Wood: Effects of Air and Palm Oil Heat Media

Lionnel Frederique Bidzanga Bessala, Jingjing Gao, Zhengbin He, Zhenyu Wang * and Songlin Yi *

Beijing Key Laboratory of Wood Science and Engineering, MOE Key Laboratory of Wooden Material Science and Application, College of Material Science and Technology, Beijing Forestry University, No. 35, Qinghua East road, Haidian District, Beijing 100083, China; lionnelbessala@gmail.com (L.F.B.B.); 18722119698@163.com (J.G.); hzbcailiao@bjfu.edu.cn (Z.H.)

* Correspondence: wangzhenyu1992@126.com (Z.W.); ysonglin@bjfu.edu.cn (S.Y.)

Abstract: The objective of this work was to study the influence of palm oil on the VOCs emitted during the heat treatment of Afromosia (*Pericopsis Elata* Van Meeuwen) and Newtonia (*Newtonia paucijuga* Harms) wood by comparing to the VOCs emitted during the heat treatment under air. Two batches of Afrormosia and Newtonia wood samples were heated under air and palm oil at temperatures of 160 °C, 180 °C, and 200 °C for 2 h. Then, the VOCs were collected by Solid Phase Micro Extraction (SPME) and measured using a Gas Chromatograph and Mass Spectrometer (GC-MS). The results showed that the temperature, the wood species, and the treatment medium have a great influence on the categories and percentages of VOCs emitted. In the air heat treatment, ethers were the most emitted VOCs from Afrormosia and Newtonia when these woods were thermally treated at 160 °C. Newtonia treated under air at 180 °C emitted more esters, while Afrormosia continued to emit more ethers under the same conditions. Moreover, Afrormosia and Newtonia treated at 200 °C emitted more ketones and aldehydes, respectively. Regarding the heat treatment of Afrormosia and Newtonia wood under palm oil, a similarity of the VOCs emitted from Newtonia with those emitted from Afrormosia under the same conditions was observed. Furthermore, palm oil was the main factor conditioning the nature of the VOCs emitted during the heat treatment. In general, for the treatment of Afrormoshia wood with palm oil, the VOCs emitted, such as alcohols, alkanes, and ethers, decreased with the treatment temperature. Ethers and ketones increased with the processing temperature. At 160 °C and 180 °C, the percentage of aldehydes was highest, while, at 200 °C, the percentage of esters was highest. Similarly, for Newtonia treated under palm oil, adehydes, ethers, and alcohols were the most abundant VOCs emitted at 160 °C. However, their percentages decreased with the increase in the treatment temperature; on the contrary, esters and ketones were weakly emitted at 160 °C and became abundant with the increase in temperature. Additionally, the ethers formed during the heat treatment of Afrormosia and Newtonia wood treated under air carry acetyl groups, while those formed during the treatment of the said wood under palm oil carry hydroxyl groups.

Keywords: Afrormosia; Newtonia; palm oil; heat treatment; VOCs

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1. Introduction

Afrormosia (*Pericopsis elata* Van Meeuwen) and Newtonia (*Newtonia paucijuga* Harms) are two imported woods from Africa, and they have attracted increasing attention for utilization. As with almost all kinds of wood, they also have shortcomings related to their low durability, dimensional instability, and high equilibrium moisture content, which can be solved by the heat treatment process [1].

Heat treatment of wood is a technique of modifying the properties of wood using heat. It has the ability to reduce the swelling, shrinkage, and equilibrium moisture content of wood [2]. In addition, this treatment improves the resistance of the wood to biotic and abiotic degradation agents. Therefore, heat treatment is acknowledged as a process that adds value to the wood trade. However, this treatment favors the emission of volatile organic compounds (VOCs) that can have a more or less negative impact on the environment [3].

Heat-treated wood emits more VOCs compared to naturally air-dried wood or non-heat-treated wood [4]. The emissions of VOCs during the heat treatment of wood depend on the nature of the wood used. Indeed, softwoods emit the highest concentrations of VOCs from wood, composed mainly of terpenes that represent about 70% of the emitted VOCs, followed by hexanal and acetic acid, whose cumulative concentrations are generally around 10% to 25% of the emitted VOCs [5]. On the contrary, hardwoods emit a greater variety of carbonyl compounds that are aldehydes, carboxylic acids, ketones, and alcohols; the main carbonyl compounds emitted are aldehydes, including hexanal, pentanal, and acetic acid [6–9]. The emissions of VOCs during the heat treatment of wood also depend on the nature of the heat transfer fluid used during the treatment [10]. For the most commonly used air medium, Sivrikaya et al. found that the most abundant VOCs, emitted from air-dried wood samples of heat-treated and vacuum-treated Scots pine, were pentanal and hexanal, which are aldehydes [11]. Hyttinen et al. investigated the effect of air heat treatment on Norway spruce, Scots pine, and European Aspen wood; they found that furfural emissions increased, while hexanal emissions decreased, for all wood species studied [12]. Xue et al. analyzed VOC emissions of heat-treated air-dried poplar wood, and the results showed that the most significant volatiles were aldehydes emitted in the furfural form [13]. Manninen et al. compared the emissions of volatile organic compounds (VOCs) from air-dried Scots pine wood and from heat-treated Scots pine wood and found that terpenes were the main VOC group emitted in the air-dried wood samples, whereas aldehydes and carboxylic acids and their esters dominated in the heat-treated wood samples [14]. Besides air, vegetable oils were also used in the heat treatment of wood in many studies because vegetable oils are good for heating due to their ability to transfer heat to wood more easily and evenly [15]. In addition, vegetable oils, in particular palm oil, have low environmental toxicity [16] and offer the possibility of adding additives, such as desiccants (to accelerate the drying of wood), during heat treatment to improve the properties of the wood [17]. However, the use of vegetable oils tends to favor the emission of VOCs in the form of aldehydes. This has been noted by authors, such as Jensen et al., who showed that oil-treated wood tends to emit predominantly VOCs belonging to the aldehyde and hydrocarbon chemical classes and attributed this observation to the influence of the oil [18]. Moreover, this VOC emission profile is very similar to those found for some vegetable oils. As well, Coughlan et al. analyzed volatile organic compounds emitted by rapeseed oil and found that most VOCs detected in the oil samples consisted, respectively, of acid, alcohol, aldehyde, ketone, benzene, ester, ether, terpene, and sulphur compounds [19]. Yang et al. identified toluene as one of the most abundant VOCs emitted during the heating of vegetable oils [20]. The emission of VOCs is therefore strongly linked to the chemical interactions between the treatment medium and the wood; it is in this logic that Wahab et al. showed that the holocellulose and cellulose percentage of wood decreases with heat treatment, while that of lignin increases [21], and these variations would be responsible for the nature of the VOCs emitted; this result was also communicated by Hill [22] and Dubey [23]. In the same vein, Bessala et al. studied, using FTIR, the variations in hemicelluloses, cellulose, and lignin in Afrormosia and Newtonia wood treated with air and palm oil at 160 °C, 180 °C, and 200 °C [24], and they found that hemicelluloses and cellulose degraded during these treatments and that there was a cleavage of β-O-4 bonds and cleavage of methoxylates from lignin. The extractives are also involved in the mechanisms leading to the emission of VOCs, and these findings have been made by authors, such as Esteves et al., who studied the changes in the content and chemical composition of Afrormosia heat-treated by the thermowood method at 212 °C for 1 h and 212 °C for 2 h [25]. The results they obtained showed that the percentage of extractives in Afrormosia wood, soluble in dichloromethane, ethanol, and water, increases as a function of temperature and duration of the thermal treatment. This trend is the same for lignin, but it reverses for cellulose and hemicelluloses. This might explain why the amount of VOC emission increases with the increasing temperature of wood modification during the heat treatment of wood [15,26].

The identification of VOCs emitted from heat-treated wood and the modification of the main wood polymers during heat treatment, especially those of Afrormosia and Newtonia, are well known [24]. However, we found very little information on the mechanisms of VOC creation during heat treatments, in particular those using palm oils as heat transfer media. This paper attempts, on the basis of experimental observations and the literature, to explain the chemical interactions between heat transfer fluids and structural polymers (hemicelluloses, cellulose, and lignin) of some African angiosperms, such as Afrormosia and Newtonia, which are responsible for the VOCs emitted during heat treatment. Such an approach contributes to a better understanding of the potential sources of production from plant biomass of chemical compounds for various applications in the industrial field.

2. Experimental

2.1. Sample Preparation

The Afrormosia (*Pericopsis elata* Van Meeuwen) and Newtonia (*Newtonia paucijuga* Harms), of African origin, that we used to make the experiment samples, were collected from the Landbond Group of China. All samples were divided into twelve groups of seven specimens, each with dimensions 100 mm × 100 mm × 20 mm (L × T × R) and with initial moisture content of approximately 60%. Specimens were dried in an oven at 103 °C ± 2 °C to absolute-dried condition before heat treatment. After drying, our samples were wrapped with aluminum foil until the heat treatment phase in order to limit the emissions of VOCs related to the extractives and likely to occur before the measurements were made. The labelling of each sample group is shown in Table 1.

Table 1. Labelling of samples treated in different conditions.

Wood Species	Heat Treatment Medium	160 °C	180 °C	200 °C
Afrormosia	Air	A-air-160	A-air-180	A-air-200
Afrormosia	Palm oil	A-oil-160	A-oil-180	A-oil-200
Newtonia	Air	N-air-160	N-air-180	N-air-200
Newtonia	Palm oil	N-oil-160	N-oil-180	N-oil-200
Palm oil Samples		Oil-160	Oil-180	Oil-200

2.2. Heat Treatment

The heat treatment of wood samples was performed in a homemade sealed heat treatment tank (Figure 1). During the heat treatment, the tank was filled with air or palm oil. In order to avoid significant heat loss, thermal insulation panels were used. Both Afromosia and Newtonia samples were heat-treated under air or palm oil medium for 2 h. The treatment temperatures were set at 160 °C, 180 °C, and 200 °C, respectively, and they were monitored by a temperature sensor. Palm oil alone has also been heated to 160 °C, 180 °C, and 200 °C. We have chosen the temperatures of 160 °C, 180 °C, and 200 °C in order to harmonize our results with those found by other researchers who have carried out similar studies [4,5,11–13,21], and, thus, we facilitated the comparison of these results. Indeed, most of the studies similar to ours, cited in this paper, refer to heat treatments of wood having been carried out at least at one of the temperatures we have chosen.

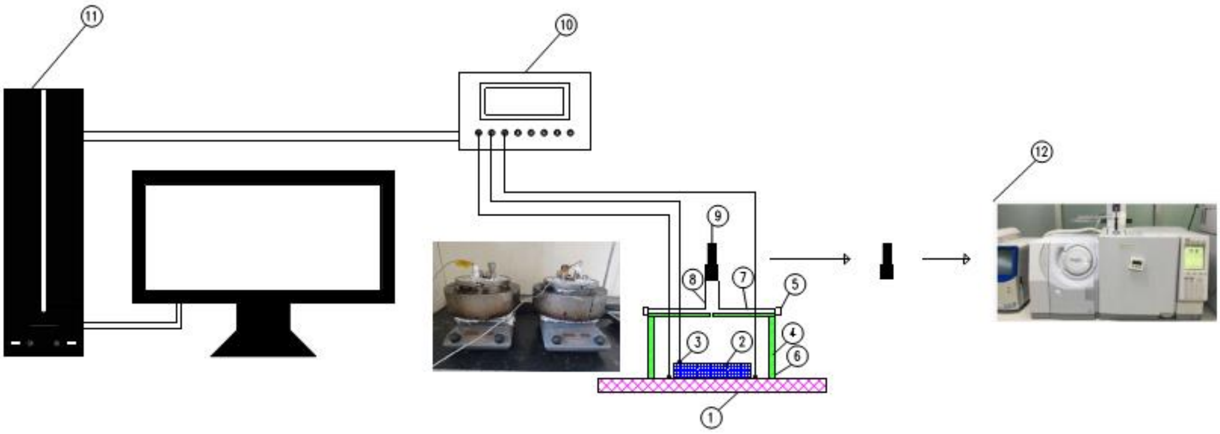


Figure 1. Wood heat treatment equipment: 1. heating plate; 2. heat treatment test material; 3. PT100 thermal resistance temperature sensor; 4. insulation material; 5. quick release buckle; 6. heat treatment tank; 7. heat treatment tank cover; 8. VOC collection port; 9. solid phase microextraction head and handle; 10. temperature inspection instrument; 11. computer; 12. GCMS.

2.3. *VOCs Measurement during Heat Treatment: GCMS*

VOCs released during wood heat treatment were measured using a Shimadzu GCMS-QP2010 Ultra Gas Chromatograph and Mass Spectrometer (Shimadzu, Japan). Before the end of the heat treatment process, the VOCs in the heat treatment tank were collected through the upper VOC collection port using a solid-phase micro extraction head for 15 min. The extraction head was then inserted into the GC-MS inlet by manual injection and desorbed for 5 min. The temperature of the chromatographic column was progressively increased as follows: (i) 45 °C for 10 min; (ii) raised to 100 °C at a rate of 3 °C/min and held for 1 min; (iii) raised to 150 °C at a rate of 5 °C/min and held for 5 min; (iv) raised to 250 °C at a rate of 10 °C/min and held for 20 min. Helium was used as the carrier gas, with a flow rate of 1 mL/min (100:1) and an EI power and electron energy of 70 eV. The mass range that we used for the mass selective detector was 45–400 m/z. The solid-phase micro extraction head was aged at 250 °C for at least 20 min before each use to remove interference from residual VOCs. The chromatograms obtained were compared to those in the NIST 2011 database to determine the categories and proportions of the related compounds. For this purpose, two main parameters were used: the retention time (RT) and the percentage of peak area (%A).

3. Results and Discussion

3.1. *Emission of VOCs from Air Heat Treatment*

The chromatogram obtained from the GCMS analysis of the air we used for the treatment of our wood showed no peak (Figure 2). This means that, compared to the VOCs emitted by the wood, those contained in the air used were negligible and were, therefore, not considered in the present study.

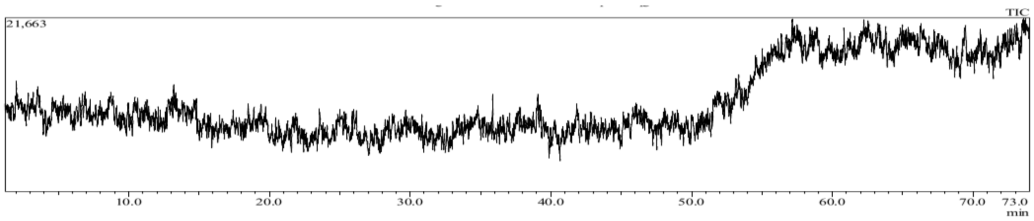


Figure 2. Air chromatogram.

VOCs emitted during the air heat treatment of Afrormosia and Newtonia woods are presented in Tables 2 and 3. They have been classified according to their chemical nature into nine groups, including alcohols, aldehydes, alkanes, ethers, esters, ketones, terpenes, pyroles, and others chemical compounds. Ethers, esters, aldehydes, ketones, and alcohols are all derived mainly from the modification of hemicelluloses, lignin, and cellulose [27]; indeed, the polysaccharides constituting the hemicelluloses of hardwoods are mainly 4-O-MethylGlucoronoXylans (MGX) [28]. These compounds have arabinose groups, which are linked to Ferulic Acid (FA) by ethers [28]. The presence of ether bonds between FA and MGX in Afrormosia and Newtonia woods is marked by the strong ring vibration at 1517 cm^{-1}, 1600 cm^{-1}, 1620 cm^{-1}, and 1690 cm^{-1} [24,28]. These bands are most pronounced for untreated Afrormosia and Newtonia wood and gradually decrease when these woods are treated at 160 °C, 180 °C, and 200 °C, respectively [24]. This shows that, for these temperature values, heat causes the bond between AF and MGX to break with the release of ethers. Comparably, ferulic acid is bound to lignin by esters [28]; in fact, feluric acid is both bound to arabinoxylane by ethers and to lignin by esters [28]. The latter binding, in the case of Afrormosia and Newtonia, is identified by the band located at 1720 cm^{-1} in the FTIR diagram of these woods [24]. This band is greater for untreated Afrormosia and Newtonia wood samples compared to those treated at 160 °C, 180 °C, and 200 °C. In other words, the heat applied to those woods at these temperatures causes the bonds between lignin and ferulic acid to break, with the release of esters. In addition, FTIR analysis of Afrormosia and Newtonia heat treated at 160 °C, 180 °C, and 200 °C allows us to identify a broad band of high intensity located between 2850 cm^{-1} and 2900 cm^{-1}, which highlights the presence of C–H bonds of aldehydes and ketones [24], characterizing also the presence of amorphous cellulose [29]. This band decreases with the increase in the treatment temperature [24]. Knowing that the endings of cellulose molecules generally contain reducing aldehydes and ketones [30], it becomes obvious that Afrormosia and Newtonia woods, when treated at 160 °C, 180 °C, and 200 °C, undergo a breakdown of the previously mentioned endings accompanied by the release of aldehydes and ketones. Similarly, the broad band of high intensity with valence vibration located between 1030 cm^{-1} and 1050 cm^{-1} show the C–OH bonds of alkohols and the C-O bonds of ethers, related to the presence of alpha-D-glucans and beta-D-glucans [29], which are nothing other than cellulose molecules. For untreated Afrormosia and Newtonia, these bands are more accentuated compared to those of the samples of said woods treated at 160 °C, 180 °C, and 200 °C [24], suggesting, therefore, that part of the alcohols and ethers emitted in the form of VOCs are generated by intramolecular mechanisms of alpha-D-glucans and beta-D-glucans due to the heat of treatment.

For the particular case of Afrormosia heat treated under air at 160 °C, 180 °C, and 200 °C, 92, 84, and 71 volatile organic compounds were, respectively, identified (Figure 3. The values shown on the chromatogram are higher than those stated because some compounds are duplicated.). 4-acetylanisole, which is by far the most emitted compound at 160 °C and 180 °C, comes from the chemical reaction between anisole, resulting from the modification of hemicelluloses, as previously explained, as well as acetylated compounds, which are available in large quantities in hardwoods [31]. 1H-pyrrole, 1-methyl can be formed by temperature-influenced cutting of the 4-O-5 bonds of lignin in the presence of argon contained in air [32]; in fact, argon is one of the constituents of ambient air. Ethanone, 2-hydroxy-1,2-bis (4-methoxyphenyl)- is also formed from lignin [33]; vanillin is derived from the oxidation of lignin by air [34]. Spiro [4.5] dec-7-ene, 1,8-dimethyl-4-(1-methylethenyl)-, [1S-(1.alpha.,4.beta.,5.alpha.)]- is an extractive [35]. It should also be noted that, at 180 °C and 200 °C of heat treatment under air of Afrormosia, we observed the presence, among the 10 most emitted VOCs, some alkanes, such as hexatriacontane and hexadecanal, some ketones, such as 2-Pentadecanone, some aldehydes, such as hexadecanal, cis-9-Hexadecenal, and some esters, such as l-(+)-Ascorbic acid 2,6-dihexadecanoate, which reflect the intensification of hemicelluloses oxidation by air, as well as the air oxidation of fatty acids [5,36].

Table 2. Main VOCs emitted during air heat treatment of Afrormosia (In order to facilitate the presentation of the results, only VOCs with a percentage area greater than or equal to 1.60% are analyzed for each treatment case, which represents at least 60% of the VOCs emitted.).

Chemical Compound	RT A-Air-160	%A A-Air-160	Chemical Classification
4-Acetylanisole	34.75	42.05	Ethers
Diisooctyl phthalate	57.42	2.85	Esters
Hexadecanoic acid, methyl ester	50.60	2.75	Esters
1H-Pyrrole, 1-methyl-	1.98	2.58	Pyrroles
Vanillin	36.24	2.54	Aldehyde
Spiro [4.5] dec-7-ene, 1,8-dimethyl-4-(1-methylethenyl)-, [1S-(1.alpha.,4.beta.,5.alpha.)]-	38.62	2.37	Terpenes
Isoledene	38.72	2.26	Terpenes
Ethanone, 2-hydroxy-1,2-bis(4-methoxyphenyl)-	56.77	2.10	Ketones
3-Furaldehyde	4.46	1.62	Aldehyde
Cedrene	36.85	1.60	Terpenes
Total		**62.72**	
Chemical compound	**RT A-air-180**	**%A A-air-180**	**Chemical Classification**
4-Acetylanisole	34.74	35.84	Ethers
2H-Cyclopropa[g]benzofuran, 4,5,5a,6,6a,6b-hexahydro-4,4,6b-trimethyl-2-(1-methylethenyl)-	47.14	6.89	Aldehydes
1H-Pyrrole, 1-methyl-	2.10	5.33	Pyrroles
Vanillin	36.25	3.02	Aldehyde
Hexatriacontane	54.68	2.21	Alkanes
Phenol, 4-ethyl-	26.52	2.00	Alcohols
2-methylhexacosane	52.70	1.89	Alkanes
Hexadecanal	46.82	1.77	Aldehydes
2-Pentadecanone	46.37	1.67	Ketones
Hexadecanoic acid, methyl ester	50.60	1.64	Esters
Total		**62.26**	
Chemical compound	**RT A-air-200**	**%A A-air-200**	**Chemical Classification**
Ethanone, 2-hydroxy-1,2-bis(4-methoxyphenyl)-	56.79	45.65	Ketones
4-Acetylanisole	34.75	11.84	Ethers
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.12	3.68	Esters
2-Propenal, 3-(4-hydroxy-3-methoxyphenyl)-	47.13	3.59	Aldehydes
3,5-Dimethoxy-4-hydroxycinnamaldehyde	51.29	3.26	Aldehyde
cis-9-Hexadecenal	53.12	2.61	Aldehydes
Vanillin	36.24	2.54	Aldehyde
Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	44.88	2.02	Aldehydes
3-Furaldehyde	4.57	2.00	Aldehydes
1-Methyl-3-pyrrolidinol	5.77	1.75	Pyrrolidines
Total		**78.94**	

Table 3. Main VOCs emitted during air heat treatment of Newtonia (Only VOCs with a percentage area greater than or equal to 1.60% are analyzed for each treatment case, which represents at least 60% of the VOCs emitted.).

Chemical Compound	RT N-Air-160	%A N-Air-160	Chemical Classification
4-Acetylanisole	34.73	21.87	Ethers
Dibutyl phthalate	50.96	6.03	Esters
Phenanthrene, 7-ethenyl-1,2,3,4,4a,4b,5,6,7,9,10,10a-dodecahydro-1,1,4a,7-tetramethyl-, [4aS-(4a.alpha.,4b.beta.,7.beta.,10a.be)]	51.62	4.51	Terpenes
Eicosane	54.68	3.99	Alkanes
1H-3a, 7-Methanoazulene, 2,3,4,7,8,8a-hexahydro-3,6,8,8-tetramethyl-, [3R-(3.alpha.,3a.beta.,7.beta.,8a.alpha.)]-(Cedr-8-ene)	36.84	3.89	Terpenes

Table 3. *Cont.*

Chemical Compound	**RT N-Air-160**	**%A N-Air-160**	**Chemical Classification**
Naphthalene, decahydro-1,1,4a-trimethyl-6-methylene-5-(3-methyl-2,4-pentadienyl)-, [4aS-(4a.alpha.,5.alpha.,8a.beta.)]-	51.19	3.84	Terpenes
Tetradecanal	43.22	3.15	Aldehydes
Heptadecanal	46.82	2.96	Aldehydes
2-Pentadecanone	46.37	2.93	Ketones
5-Octadecene, (E)-	46.25	2.40	Alkenes
Hexadecanoic acid, methyl ester	50.60	2.27	Esters
Triethylamine	1.44	2.08	Amines
Hexatriacontane	56.97	2.03	Alkanes
1,2-Benzenedicarboxylic acid, bis(2-methylpropyl) ester	49.59	2.01	Esters
Cyclodecane, methyl-	46.27	2.01	Alkanes
Pentacyclo [9.1.0.0(2,4).0(5,7).0(8,10)] dodecane, 3,3,6,6,9,9,12,12-octamethyl-, anti,anti,anti-	47.14	1.92	Alkanes
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.08	1.72	Esters
Hexadecanoic acid, ethyl ester	51.48	1.65	Esters
Total		**71.26**	
Chemical compound	**RT N-air-180**	**%A N-air-180**	**Chemical Classification**
3-Furaldehyde	4.55	8.64	Aldehydes
Phenol, 2,6-dimethoxy-4-(2-propenyl)-	46.32	5.25	Alcohols
Phenol, 2,6-dimethoxy-	34.60	4.71	Alcohols
Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	44.88	4.35	Aldehydes
Vanillin	36.24	4.16	Aldehydes
2-Propenal, 3-(4-hydroxy-3-methoxyphenyl)-	47.14	3.96	Aldehydes
Hexadecanoic acid, ethyl ester	51.48	3.81	Esters
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.11	3.71	Esters
Hexadecanoic acid, methyl ester	50.60	3.23	Esters
trans-Isoeugenol	37.88	3.19	Esters
3,5-Dimethoxy-4-hydroxycinnamaldehyde	51.30	3.15	Aldehydes
4-Acetylanisole	34.75	2.28	Ethers
2-Nonadecanone	46.38	2.18	Ketones
(E,E)-7,11,15-Trimethyl-3-methylene-hexadeca-1,6,10,14-tetraene	50.41	2.07	Terpenes
Phenanthrene, 7-ethenyl-1,2,3,4,4a,4b,5,6,7,9,10,10a-dodecahydro-1,1,4a,7-tetramethyl-, [4aS-(4a.alpha.,4b.beta.,7.beta.,10a.be)]	51.62	2.00	Terpenes
(E)-9-Octadecenoic acid ethyl ester	53.39	1.98	Esters
Methyl stearate	52.98	1.88	Esters
1-Naphthalenepropanol, .alpha.-ethenyldecahydro-.alpha.,5,5,8a-tetramethyl-2-methylene-, [1S-[1.alpha.(S*),4a.beta.,8a.alpha.]]	51.20	1.87	Terpenes
2-methylhexacosane	48.66	1.74	Alkanes
Hexatriacontane	54.69	1.70	Alkanes
Pentadecanal-	46.84	1.69	Aldehydes
Pentadecanoic acid, ethyl ester	53.66	1.66	Esters
6-Octadecenoic acid, methyl ester	52.70	1.62	Esters
Total		**70.83**	
Chemical compound	**RT N-air-200**	**%A N-air-200**	**Chemical Classification**
4-Acetylanisole	34.75	12.16	Ethers
3-Furaldehyde	4.58	7.76	Aldehydes
2-Pentadecanone	46.39	7.03	Ketones
Phenol, 2,6-dimethoxy-	46.84	5.81	Alcohols
Pentadecanal-	46.84	5.67	Aldehydes
Vanillin	36.26	5.22	Aldehydes
trans-Isoeugenol	37.88	5.05	Esters

Table 3. *Cont.*

Chemical Compound	RT N-Air-160	%A N-Air-160	Chemical Classification
Tetradecanal	43.25	4.49	Aldehydes
11-Octadecenoic acid, methyl ester	34.13	3.89	Esters
Dodecanal	36.78	3.00	Aldehydes
Mequinol	21.56	2.58	Alcohols
Hexadecanoic acid, methyl ester	50.61	2.03	Esters
Cyclodecane, methyl-	46.27	2.01	Alkanes
Total		**66.70**	

Figure 4 shows the evolution of the VOC classes emitted during the heat treatment of Afrormosia wood under air as a function of temperature. It can be seen, from this figure, that, for the temperatures of treatment at 160 °C and 180 °C, the class of VOCs most abundantly emitted is that of the ethers, but the emission of this chemical class of VOCs decreased with temperature. We have already shown that the main ether emitted was 4-Acetylanisole, whose production in wood depends on our temperature range regarding the available quantity of bonds between hemicelluloses and lignin through ferulic acid; however, this availability decreases sharply with increasing processing temperature [37], which could justify the decrease in the content of emitted ethers. The emissions of aldehydes and ketones increased with temperature. In wood, some hemicelluloses chains contain aldehyde groups, and they are called hemialdales; when these are heated to temperatures higher than 105 °C, the aldehyde groups are progressively released, which explains their increase with the temperature of heat treatment [38]. Bessala et al. attributed the presence of these aldehyde groups in Afrormosia and Newtonia woods to the fine band of high intensity observed around wavelength 1740 cm^{-1} of the related FTIR diagram [24]. The formation of aldehydes and ketones can also derive from wood triglycerides; the latter compounds, in the presence of water molecules contained in the wood, can hydrolyze to form unsaturated fatty acids, such as palmitic acid and others [26], which, in turn, can be oxidized by air oxygen to produce either aldehydes or ketones [39]. It is worth mentioning that the oxidation of unsaturated acids in wood is favored by increasing temperature and heat treatment time [25,40], which could explain why the emission of aldehydes and ketones increases with increasing processing temperature. The alcohols emitted during the heat treatment of Afrormosia are mostly phenolic in nature and increased with the rising of temperature (Table 2). These compounds can exist in the wood in small quantities as extractives [25]; however, they can also be produced by the oxidation of lignin [41], which occurs gradually with an increase in temperature [5]. In other words, for low temperatures, the oxidation of lignin is carried out weakly, but it increases with the elevation of the temperature, which is manifested by the small emissions of alcohols of phenolic nature that, however, increase with the temperature. Regarding terpenes, we observed that their emissions decreased with the treatment temperature. In fact, terpenes are secondary metabolites located in the wood channels; their evacuation towards the outside of the wood is facilitated by the temperature, which simultaneously leads to a decrease in the content in the said channels [42]. Thus, their influence on the VOC profile for the heat treatment under air would depend much more on the temperature and not on the processing media.

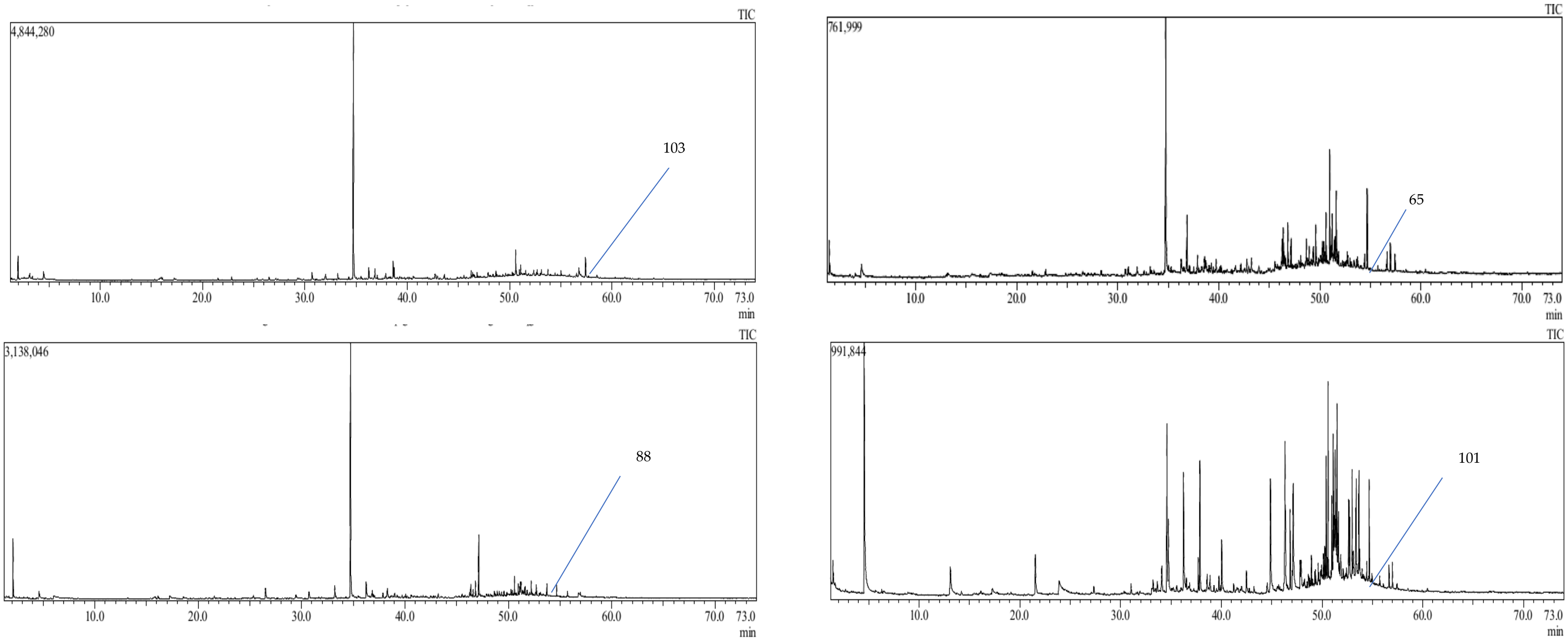
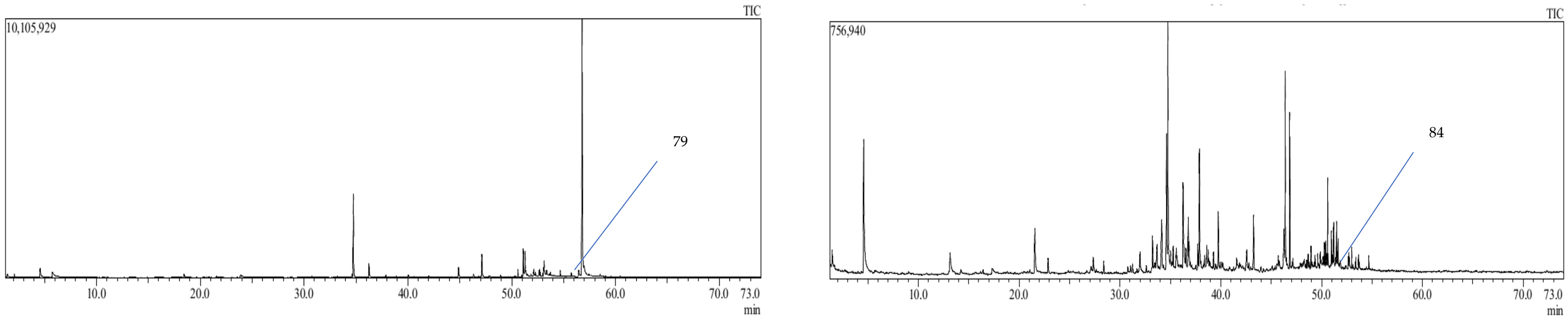


Figure 3. *Cont*.



(**a**) (**b**)

Figure 3. Total ion chromatogram of Afrormosia (**a**) and Newtonia (**b**) heat treated under air at 160 °C, 180 °C, and 200 °C (from top to bottom, respectively).

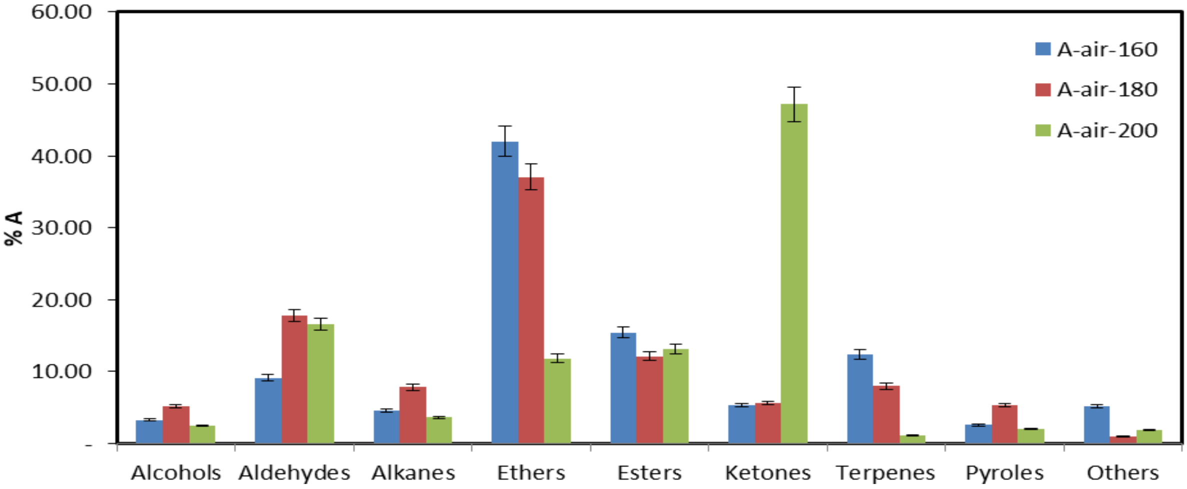


Figure 4. Class of VOC chemical compound evolution with the temperature of air-treated Afrormosia.

At temperatures of 160 °C, 180 °C, and 200 °C, 61, 89, and 76 volatile organic compounds were, respectively, identified during the heat treatment of Newtonia under air (Figure 3. The values shown on the chromatogram are higher than those stated because some compounds are duplicated). Table 3 shows that, similar to Afrormosia, 4-acetylanisole and dibutyl phthalate are the most emitted compounds during heat treatment of Newtonia wood at 160 °C under air, as well. From the VOC proportion of different categories shown in Figure 5, ethers were the most emitted compounds at 160 °C, but their content decreased for the treatment performed at 180 °C, and then their content increased again to the point that 4-acetylanisole was the most emitted VOC for the heat treatment of Newtonia at 200 °C. The gradual decrease in the number of alkanes and terpenes emitted with temperature was also observed. Aldehydes and ketones gradually increased with the treatment temperature; moreover, at 180 °C, it was mainly 3-furaldehyde that was the most emitted VOC, and, at 200 °C, it was the aldehyde chemical class that was the most emitted among the VOCs detected at said temperature [13]. Esters, at 160 °C, were emitted in almost the same amount as ethers, and then they became the most emitted VOC chemical class for Newtonia processing at 180 °C before starting a reduction in content. Newtonia wood emitted more alkohols, aldehydes, alkanes, esters, and terpenes than Afrormosia wood during the heat treatment in air; however, it emitted less ethers and ketones. Based on this observation, it can be stated that Newonia wood would oxidize more than Afrormosia wood under the effect of air during heat treatment.

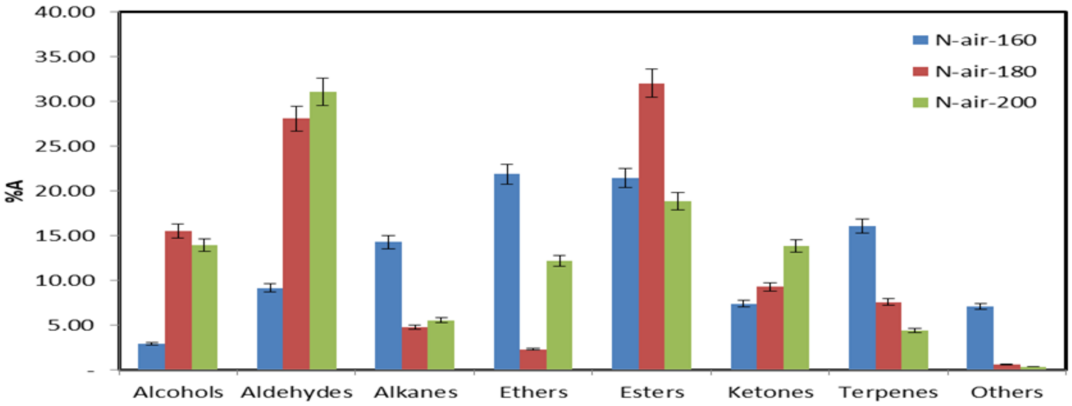


Figure 5. Class of VOC chemical compound evolution with temperature of air-treated Newtonia.

3.2. Emission of VOCs from Palm Oil Heat Treatment

In order to evaluate the influence of palm oil on the profiles of VOCs emitted during the heat treatment of palm oil from Afrormosia and Newtonia wood, VOCs emitted during the heating of palm oil were taken separately. The results show that the VOCs emitted during the heating of palm oil at 160 °C, 180 °C, and 200 °C can be classified into eight categories (Figure 6), including: alcohols, aldehydes, alkanes, esters, ethers, ketones, terpenes, and others. The percentage of alcohols decreased with temperature. The same trend was observed for aldehydes, alkanes, ethers, and terpenes. For esters and ketones, the percentages increased with temperature. These results are consistent with those found by Giuffrè et al. [43]. Table 4 shows the most emitted VOCs for each palm oil heating temperature. It appears that, at 160 °C, 2,4-decadienal is the most emitted VOC from palm oil, while, at 180 °C and 200 °C, l-(+)-ascorbic acid 2,6-dihexadecanoate is the most emitted.

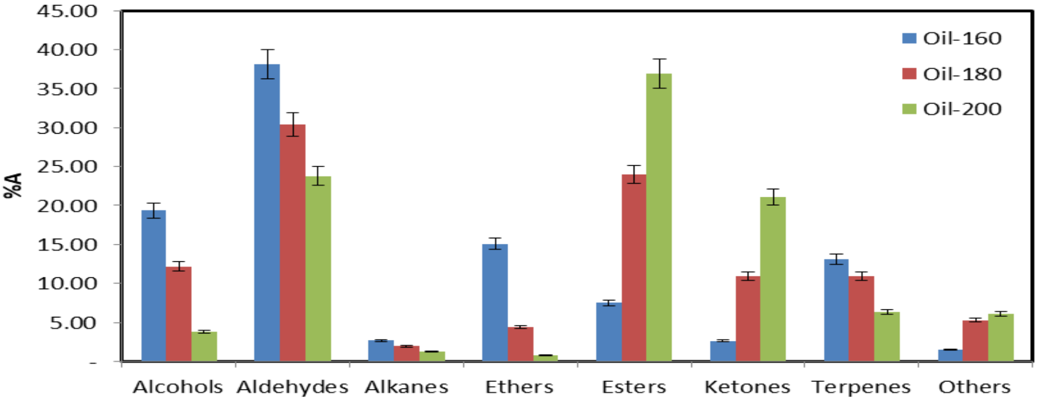


Figure 6. Class of VOCs chemical compound evolution with temperature of heated palm oil.

During the palm oil heat treatment of Afrormosia wood, volatile organic compounds were identified and grouped into alcohols, aldehydes, alkanes, ethers, esters, ketones, terpenes, and other compounds [44]; 35, 41, and 45 volatile organic compounds were identified at 160 °C, 180 °C, and 200 °C, respectively (Figure 7. The values shown on the chromatogram are higher than those stated because some compounds are duplicated.). Table 5 shows the main volatile organic compounds emitted during the heat treatment of Afromosia wood with palm oil. A similarity of emissions to those observed during oil heating was noted. Indeed, all the 10 main VOCs emitted during the heat treatment of Afrormosia wood under palm oil at 160 °C were also observed among the 10 most emitted VOCs when palm oil was heated at the same temperature. Moreover, for Afrormosia treated at 160 °C, the phenolic alcohols 3-tert-butyl-4-hydroxyanisole, butylated hydroxytoluene, and phenol, 3-(1,1-dimethylethyl)-4-methoxy- have higher percentage areas than those observed when heating the oil at 160 °C. This suggests a generation of these alcohols from the chemical components of the wood, especially lignin, because it is by nature a polyphenol [45]. More explicitly, lignin consists of three basic phenolic units: coniferyl alcohol, synapyl alcohol, and p-coumaryl alcohol. Under the effect of temperature, these units can split at their lateral macromolecular chains and produce ethers and alcohols [45]. For the specific case of the extra 3-tert-butyl-4-hydroxyanisole, the emission of this compound is also correlated to the modification of hemicelluloses that produce a certain amount of anisoles, as explained in Section 3.1; these subsequently undergo molecular rearrangements with other compounds, among which those with hydroxyl groups form 3-tert-butyl-4-hydroxyanisole [31]. Emissions of 2,4-decadienal and 2,4-decadienal (E,E) were slightly increased compared to observations when the oil was heated to 160 °C, and this would likely be due to lignin-related chemical processes [20]. Excess 2,4-decadienal would also come from the oxidation by palm oil of linoleic acid, resulting from the modification of hemicelluloses and cellulose [46].

Table 4. Main VOCs emitted during palm oil heating (only VOCs with a percentage area greater than or equal to 1.60% are presented for each treatment case which represents at least 60% of the VOCs emitted).

Chemical Compound	**RT Oil-160**	**%A Oil-160**	**Chemical Classification**
2,4-Decadienal	33.60	21.39	Aldehyde
3-tert-Butyl-4-hydroxyanisole	39.13	15.09	Ethers
Butylated Hydroxytoluene	39.48	11.93	Alcohol
Epicedrol	42.98	9.06	Terpenes
2,4-Decadienal, (E,E)-	32.67	6.17	Aldehyde
2-Undecenal	35.29	4.82	Aldehyde
Benzyl alcohol	18.52	3.76	Alcohol
Phenol, 3-(1,1-dimethylethyl)-4-methoxy-	38.80	3.09	Alcohol
Hexadecanoic acid, methyl ester	50.61	2.89	Esters
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.12	2.83	Esters
Nonanal	22.89	1.72	Aldehyde
Total		**82.75**	
Chemical compound	**RT oil-180**	**%A oil-180**	**Chemical Classification**
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.15	14.37	Esters
2,4-Decadienal	33.61	14.16	Aldehyde
2-Undecenal	35.30	7.02	Aldehyde
Epicedrol	43.00	6.10	Terpenes
Butylated Hydroxytoluene	39.49	5.11	Alcohol
3-tert-Butyl-4-hydroxyanisole	39.14	4.38	Ethers
Hexadecanoic acid, methyl ester	50.62	4.35	Esters
2H-Pyran-2-one, tetrahydro-6-nonyl-	53.09	3.02	Ketone
2-Pentadecanone	46.40	2.58	Ketone
2(3H)-Furanone, 5-dodecyldihydro-	52.75	2.26	Ketone
Phenol, 3-(1,1-dimethylethyl)-4-methoxy-	38.81	2.20	Alcohol
Nonanal	22.91	1.85	Aldehyde
trans-4,5-Epoxy-(E)-2-decenal	35.83	1.73	Aldehyde
2-Hexen-1-ol, 2-ethyl-	35.03	1.61	Alcohol
Total		**70.74**	
Chemical compound	**RT oil-200**	**%A oil-200**	**Chemical Classification**
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.18	23.12	Esters
2-Undecenal	35.29	7.04	Aldehyde
2,4-Decadienal	33.60	4.55	Aldehyde
2(3H)-Furanone, dihydro-5-tetradecyl-	52.75	4.39	Ketone
2H-Pyran-2-one, 6-hexyltetrahydro-	53.09	4.18	Ketone
Cyclopentadecanone, 2-hydroxy-	53.13	3.56	Ketone
2-Pentadecanone	46.40	3.40	Ketone
Hexadecanoic acid, methyl ester	50.61	3.22	Esters
Epicedrol	42.99	2.96	Terpenes
trans-4,5-Epoxy-(E)-2-decenal	35.83	2.19	Aldehyde
Tetradecanal	36.79	1.76	Aldehyde
Total		**60.37**	

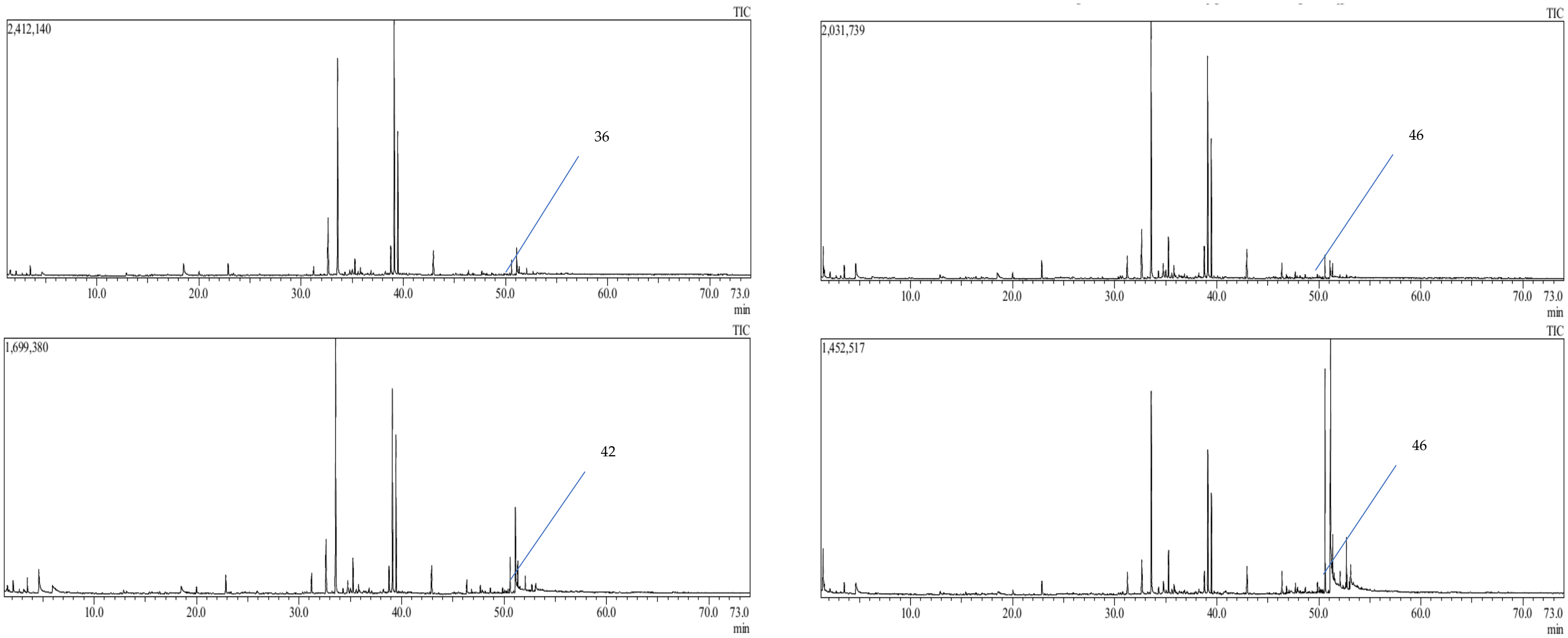
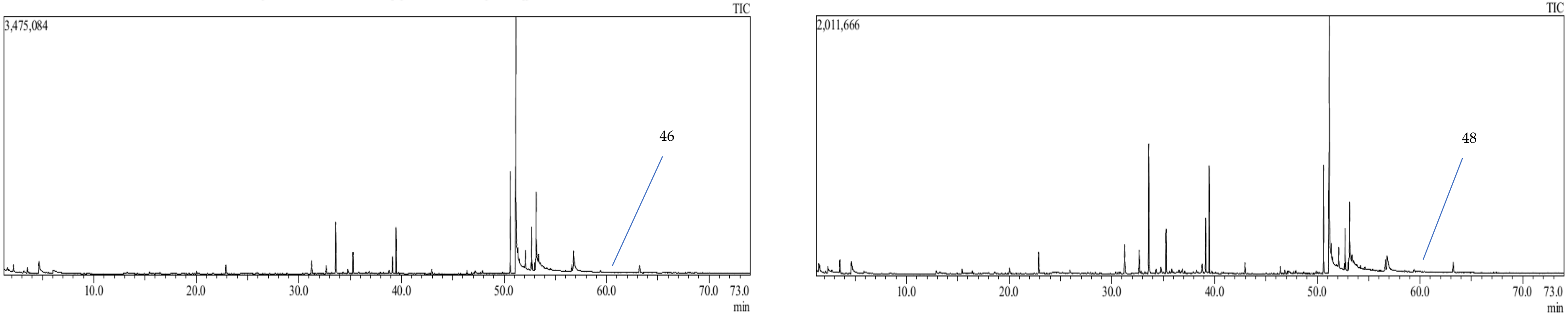


Figure 7. *Cont*.



(**a**) (**b**)

Figure 7. Total ion chromatogram of Afrormosia (**a**) and Newtonia (**b**) heat treated under palm oil at 160 °C, 180 °C, and 200 °C (from top to bottom, respectively).

Table 5. Main VOCs emitted during palm oil heat treatment of Afrormosia (only VOCs with a percentage area greater than or equal to 1.60% are analyzed for each treatment case, which represents at least 60% of the VOCs emitted).

Chemical Compound	**RT A-Oil-160**	**%A A-Oil-160**	**Chemical Classification**
3-tert-Butyl-4-hydroxyanisole	39.11	26.06	Ethers
2,4-Decadienal	33.57	25.53	Aldehydes
Butylated Hydroxytoluene	39.46	14.10	Alcohols
2,4-Decadienal, (E,E)-	32.64	7.01	Aldehydes
Epicedrol	42.95	3.58	Terpenes
Phenol, 3-(1,1-dimethylethyl)-4-methoxy-	38.78	3.33	Alcohols
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.10	2.98	Esters
2-Undecenal	35.26	2.88	Aldehydes
Benzyl alcohol	18.49	2.73	Alcohols
Nonanal	22.87	1.62	Aldehydes
Total		**89.82**	
Chemical compound	**RT A-oil-180**	**%A A-oil-180**	**Chemical Classification**
2,4-Decadienal	33.57	23.06	Aldehydes
3-tert-Butyl-4-hydroxyanisole	39.10	16.43	Ethers
Butylated Hydroxytoluene	39.46	12.49	Alcohols
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.11	7.95	Esters
2,4-Decadienal, (E,E)-	32.64	5.33	Aldehydes
2-Undecenal	35.26	4.95	Aldehydes
3-Furaldehyde	4.60	4.14	Aldehydes
Cedrol	42.94	3.37	Terpenes
Phenol, 3-(1,1-dimethylethyl)-4-methoxy-	38.77	2.44	Alcohols
Nonanal	22.85	2.07	Aldehydes
Hexadecanoic acid, methyl ester	50.60	2.03	Esters
Total		**84.26**	
Chemical compound	**RT A-oil-200**	**%A A-oil-200**	**Chemical Classification**
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.16	35.32	Esters
Cyclopentadecanone, 2-hydroxy-	53.13	11.59	Ketones
Hexadecanoic acid, methyl ester	50.60	6.90	Esters
2,4-Decadienal	33.58	5.96	Aldehydes
Ethanone, 2-hydroxy-1,2-bis(4-methoxyphenyl)-	56.77	4.35	Ketones
Butylated Hydroxytoluene	39.47	4.26	Alcohols
2-Undecenal	35.27	3.92	Aldehydes
1-(4-Undecylphenyl) ethanone	51.35	3.61	Ketones
6-Octadecenoic acid, methyl ester, (Z)-	52.69	2.94	Esters
3-Furaldehyde	4.65	2.41	Aldehydes
Octadecanoic acid	53.36	2.38	Esters
Docosanoic acid, ethyl ester	51.48	1.79	Esters
Hexadecanoic acid, trimethylsilyl ester	52.08	1.66	Esters
3-tert-Butyl-4-hydroxyanisole	39.12	1.60	Ethers
Total		**88.69**	

The emission of nonanal is mainly due to the oxidation of nonanoic acid from palm oil [44], as its content during the treatment of Afrormosia with oil at 160 °C is identical to that observed during the heating of palm oil at the same temperature; similarly, the emissions of l-(+)-ascorbic acid 2,6-dihexadecanoate and benzyl alcohol are exclusively due to palm oil. For heat treatment under oil at 180 °C of Afrormosia wood, the amounts of 2,4-decadienal, 3-tert-butyl-4-hydroxyanisole, and butylated hydroxytoluene emitted are higher than those emitted during the heating of palm oil under the same conditions; and, the mechanisms of emission of the observed excess amounts of these compounds were explained in the previous paragraph. The emissions of l-(+)-ascorbic acid 2,6-dihexadecanoate, 2-undecenal, cedrol, phenol, 3-(1,1-dimethylethyl)-4-methoxy-, and nonanal are mainly from palm oil; in the case of the heat treatment of Afrormosia wood at 180 °C under air, the above-mentioned compounds were emitted only in trace amounts. The increase in the proportions of 3-furaldehyde during the heat treatment of Afrormosia wood under palm oil reflects the thermal modification of hemicelluloses, mainly D-Xylose and arabinose [27]. Regarding the heat treatment under oil of Afrormosia wood at 200 °C, the appearance of four new compounds among the 10 most emitted VOCs were noted compared to those emitted under the other temperatures. These are cyclopentadecanone, 2-hydroxy, Ethanone, 2-hydroxy-1,2-bis (4-methoxyphenyl)-, 1-(4-Undecylphenyl) ethanone, and 6-octadecenoic acid, methyl ester, (Z)-. Cyclopentadecanone is thought to be produced by the high-temperature chemical reaction between acid methyl ester and xylene from wood xylose [47,48]. Ethanone, 2-hydroxy-1,2-bis(4-methoxyphenyl)-, and 1-(4-Undecylphenyl) would be derived from the depolymerization of p-hydroxyphenyl and guaiacyl units of lignin [33]. Finally, 6-octadecenoic acid, methyl ester, (Z) is thought to be derived from the degradation of hemicelluloses at high temperature (Section 3.1). Overall, as shown in Figure 8, for the treatment of Afrormosia wood with palm oil, the VOCs emitted, such as alcohols, alkanes, and ethers, decreased with the treatment temperature. The esters and ketones increased with the processing temperature. At 160 °C and 180 °C, the percentage of aldehydes was highest, while, at 200 °C, the percentage of esters was highest [49].

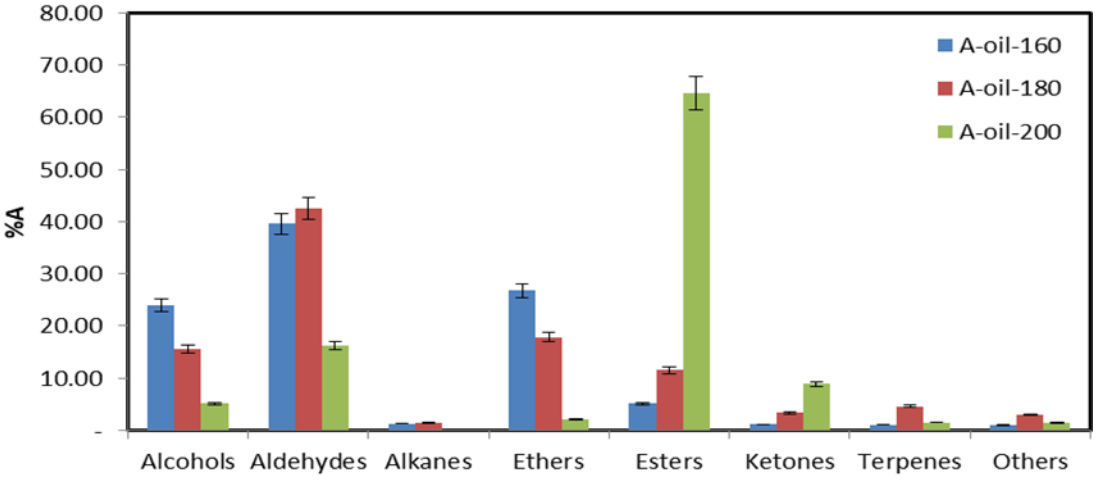


Figure 8. Class of VOCs chemical compound evolution with temperature of Afrormosia heated-treated under palm oil.

Concerning the emission of VOCs from palm oil heat treatment of *Newtonia paucijuga* (Harms), 44 compounds were observed for the 160 °C treatment, 46 compounds were identified for the 180 °C treatment, and 48 compounds were emitted for the 200 °C treatment (Figure 7. The values shown on the chromatogram are higher than those stated because some compounds are duplicated.). Table 6 shows the main VOCs emitted during the palm oil heat treatment of this wood. Comparing this table with Table 5, we observed a similarity in the VOCs emitted during the palm oil treatment of Newtonia with those emitted during the treatment of Afrormosia under the same conditions. In addition, although palm oil is still the main factor conditioning the VOCs emitted during the heat treatment of Newtonia wood with palm oil, which is indicated by the similarity in the classifications of compounds, the VOCs profiles in Newtonia wood heat treatment with palm oil also shown their own features. Thus, for the heat treatment under palm oil at 160 °C of Newtonia wood, the presence of 3-furaldehyde was noticed, which is almost non-existent in the emissions of VOCs during the heating of palm oil, except at 160 °C. In fact, the 3-furaldehyde compound results from the degradation of hemicelluloses, in particular xyloses, such as pentose [50]. Moreover, it was found that the emission of 3-fulareldehyde does not depend on the treatment medium, but rather on the treatment temperature. In other words, whether for Newtonia or Afrormosia, treated with air or palm oil, we observed the emission of 3-furaldehyde except at certain temperatures, as described by Tables 2, 3, 5 and 6. Concerning the heat treatment under palm oil at 180 °C of Newtonia wood, the main difference from the emissions observed during the heat treatment of Afrormosia and heating of the oil under the same conditions is the presence of propanamide, N-(1-ethyl-1,2,3,4-tetrahydro-2,2,4-trimethyl-7-quinolinyl)- [51]. For the heat treatment of Newtonia wood under oil at 200 °C, we observed exactly the same VOCs as those emitted during the treatment of Afrormosia wood under the same conditions with a preponderance of l-(+)-ascorbic acid 2,6-dihexadecanoate.

Table 6. Main VOCs emitted during palm oil heat treatment of *Newtonia paucijuga*.

Chemical Compound	**RT N-Oil-160**	**%A N-Oil-160**	**Chemical Classification**
2,4-Decadienal	33.58	25.37	Aldehydes
3-tert-Butyl-4-hydroxyanisole	39.11	19.20	Ethers
Butylated Hydroxytoluene	39.46	11.55	Alcohols
2-Undecenal	35.27	6.18	Aldehydes
2,4-Decadienal, (E,E)-	32.64	5.35	Aldehydes
Epicedrol	42.95	3.71	Terpenes
Phenol, 3-(1,1-dimethylethyl)-4-methoxy-	38.78	3.06	Alcohols
3-Furaldehyde	4.63	2.54	Aldehydes
Tetraethyl ammonium fluoride	1.45	2.23	
Nonanal	22.86	1.99	Aldehydes
4-Acetylanisole	34.75	1.74	Ethers
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.10	1.71	Esters
Total		**84.63**	
Chemical compound	**RT N-oil-180**	**%A N-oil-180**	**Chemical Classification**
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.14	20.87	Esters
2,4-Decadienal	33.58	18.20	Aldehydes
Hexadecanoic acid, methyl ester	50.61	10.53	Esters
3-tert-Butyl-4-hydroxyanisole	39.12	9.23	Ethers
Butylated Hydroxytoluene	39.47	6.42	Alcohols
2-Undecenal	35.28	4.76	Aldehydes
Propanamide, N-(1-ethyl-1,2,3,4-tetrahydro-2,2,4-trimethyl-7-quinolinyl)-	51.35	3.48	
Epicedrol	42.97	2.73	Terpenes
Tetraethyl ammonium fluoride	1.43	2.52	
Cyclopentadecanone, 2-hydroxy-	53.12	2.49	Ketones
9-Octadecenoic acid, methyl ester, (E)-	52.70	2.41	Esters
2-Pentadecanone	46.39	1.71	Ketones
Phenol, 3-(1,1-dimethylethyl)-4-methoxy-	38.79	1.66	Alcohols
Total		**87.01**	
Chemical compound	**RT N-oil-200**	**%A N-oil-200**	**Chemical Classification**
l-(+)-Ascorbic acid 2,6-dihexadecanoate	51.15	24.76	Esters
2,4-Decadienal	33.58	11.71	Aldehydes
Cyclopentadecanone, 2-hydroxy-	53.13	7.85	Ketones
Butylated Hydroxytoluene	39.47	7.74	Alcohols
2-Undecenal	35.28	6.30	Aldehydes
Hexadecanoic acid, methyl ester	50.60	5.91	Esters
3-tert-Butyl-4-hydroxyanisole	39.12	4.03	Ethers
Ethanone, 2-hydroxy-1,2-bis(4-methoxyphenyl)-	56.79	3.02	Ketones
1-(4-Undecylphenyl) ethanone	51.35	2.66	Ketones
9-Octadecenoic acid (Z)-, methyl ester	52.70	2.63	Esters
2,4-Decadienal, (E,E)-	32.66	2.30	Aldehydes
Nonanal	22.88	2.13	Aldehydes
Octadecanoic acid	53.37	2.02	Esters
3-Furaldehyde	4.65	1.62	Aldehydes
Total		**84.68**	

In general, aldehydes, ethers, and alcohols are the most abundant VOCs emitted at 160 °C. However, their percentages decrease with the increase in treatment temperature; on the contrary, esters and ketones are weakly emitted at 160 °C and become abundant with the increase in temperature. Moreover, at 200 °C, esters are the most abundantly emitted, followed by aldehydes and ketones (Figure 9). This would be due to the degradation of hemicelluloses, which, in hardwoods, contain more acetyl groups [52,53]. The ethers formed during the heat treatment of Afrormosia and Newtonia wood treated under air carry acetyl groups, while those formed during the treatment of said wood under palm oil carry hydroxyl groups. The treatments under air induce a significant production of vanilin and ketones, which, respectively, indicate the oxidation of lignin by air; and the oxidation by air of the unsaturated fatty acids contained in a remarkable way in species of wood, such as Afrormosia; In addition, there is also a preponderance of emission of certain terpenic compounds, contrary to the treatments under palm oil, which favor, rather, the emission of esters and aldehydes, resulting from the scission under the effect of the temperature of the unsaturated fatty acids contained in the aforementioned oil.

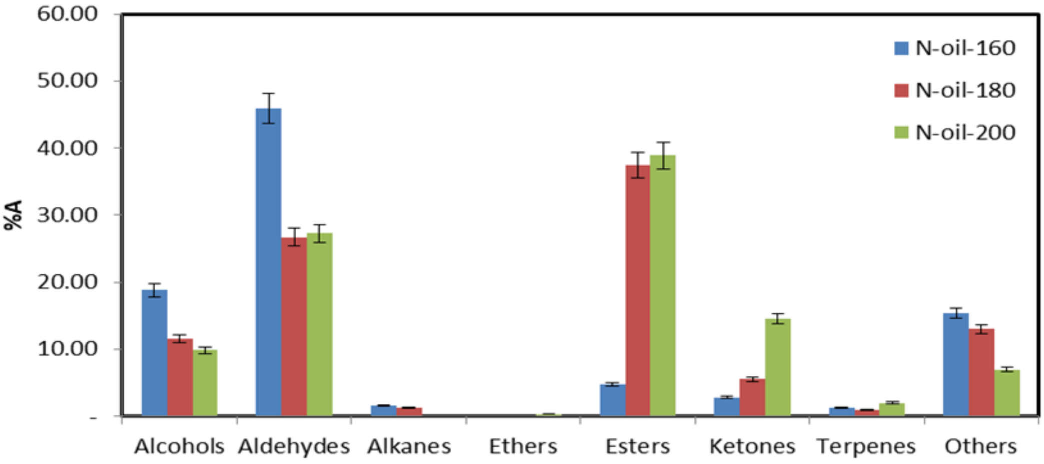


Figure 9. Class of VOC chemical compound evolution with temperature of Newtonia heat-treated under palm oil.

4. Conclusions

The main objective of this study was to investigate the influence of palm oil on VOCs emitted during the heat treatment of Afromosia (*Pericopsis Elata* Van Meeuwen) and *Newtonia paucijuga* (Harms) woods, compared to VOCs emitted during the heat treatment under the air of these woods. The results showed that the temperature, the wood species, and the treatment medium have a great influence on the categories and relative contents of VOCs. Indeed, ethers were the VOCs most emitted by Afrormosia and Newtonia when these woods were thermally treated under air at 160 °C. Newtonia treated under air at 180 °C emitted more esters, while Afrormosia treated under the same conditions continued to emit more ethers. In addition, Afrormosia and Newtonia thermally treated under air at 200 °C emitted more ketones and aldehydes, respectively. Regarding the heat treatment of Afrormosia and Newtonia wood under palm oil, we observed a similarity in the VOCs emitted during the treatment of Newtonia under palm oil as compared to those emitted during the treatment of Afrormosia under the same conditions. In fact, aldehydes, ethers, and alcohols were the most abundant VOCs emitted at 160 °C and 180 °C, while the percentage of esters was highest at 200 °C. In addition, palm oil was the main factor conditioning the nature of the VOCs emitted during the heat treatment of Afrormosia and Newtonia wood with palm oil. Overall, for the treatment of Afrormosia wood with palm oil, the VOCs emitted, such as alcohols, alkanes, and ethers, decreased with the treatment temperature. Esters and ketones increased with the temperature. These observations were explained through chemical interactions between heat media and wood components such as hemilcelluloses, cellulose, and lignin. Thus, in the process of recycling VOCs from the thermal treatment of wood, Newtonia and Afromosia treated under air are more suitable for the production of ethers and ketones from plant biomass, while the same woods treated under palm oil are more suitable for the production of aldehydes and esters.

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References

1. Edvardsen, K.; Sandland, K. Increased drying temperature: Its influence on the dimensional stability of wood. *Holz Als Roh Und Werkst.* **1999**, *57*, 207–209. [CrossRef]
2. Navickas, P.; Albrektas, D. Effect of Heat Treatment on Sorption Properties. *Mater. Sci.* **2013**, *19*, 291–294.
3. Esteves, B.M.; Pereira, H. Wood modification by heat treatment: A revew. *BioResources* **2009**, *4*, 370–404. [CrossRef]
4. Cech, P. Comparison of VOC emissions from natural wood and heat treated wood. *Drv. Ind.* **2018**, *69*, 297–309. [CrossRef]
5. Pohleven, J. Volatile organic compounds emitted from untreated and thermally modified wood-a review. *Wood Fiber Sci.* **2019**, *51*, 231–254. [CrossRef]
6. Roffael, E. Volatile Organic Compounds and Formaldehyde in Nature, Wood and Wood Based Panels. *Holz Als Roh Und Werkst.* **2006**, *64*, 144–149. [CrossRef]
7. Peters, D.H.; Garg, A.; Bloom, G.; Walker, D.G.; Brieger, W.R.; Rahman, M.H. Poverty and access to health care in developing countries. *Ann. N. Y. Acad. Sci.* **2008**, *1136*, 161–171. [CrossRef]
8. Waliszewska, B.; Zborowska, M.; Dukiewicz, H.; Wojciechowski, T.W.; Cofta, G. Identification of volatile organic compounds emitted from meranti and larch wood. *For. Wood. Technol.* **2013**, *84*, 262–268.
9. Hofmann, T.; Wetzig, M.; Retfalvi, T.; Sieverts, T.; Bergemann, H.; Niemz, P. Heat-treatment with the vacuum-press dewatering method: Chemical properties of the manufactured wood and the condensation water. *Eur. J. Wood Prod.* **2013**, *71*, 121–127. [CrossRef]
10. Ding, T.; Gu, L.; Liu, X. Influence of steam pressure on chemical changes of heat-treated mongolian pine wood. *Bioresources* **2011**, *6*, 1880–1889.
11. Sivrikaya, H.; Tesařová, D.; Jeřábková, E.; Can, A. Color change and emission of volatile organic compounds from Scots pine exposed to heat and vacuum-heat treatment. *J. Build. Eng.* **2019**, *26*, 100918. [CrossRef]
12. Hyttinen, M.; Masalin-Weijo, M.; Kalliokoski, P.; Pasanen, P. Comparison of voc emissions between air-dried and heat-treated norway spruce (picea abies), scots pine (pinus sylvesteris) and european aspen (populus tremula) wood. *Atmos. Environ.* **2010**, *44*, 5028–5033. [CrossRef]
13. Xue, L.; Zhao, Z.; Zhang, Y.; Chu, D.; Mu, J. Analysis of gas chromatography -mass spectrometry coupled with dynamic headspace samples on volatile organic compounds of heat-treated poplar at high temperatures. *Bioresources* **2016**, *11*, 3550–3560. [CrossRef]
14. Manninen, A.; Pasanen, P.; Holopainen, J. Comparing the VOC emissions between air-dried and heat-treated Scots pine wood. *Atmos. Environ.* **2002**, *36*, 1763–1768. [CrossRef]
15. Cheng, D.; Chen, L.; Jiang, S.; Zhang, Q. Oil Uptake Percentage in Oil-Heat-Treated Wood, its Determination by Soxhlet Extraction, and its Effects on Wood Compression Strength Parallel to the Grain. *BioResources* **2014**, *9*, 120–131. [CrossRef]
16. Court, M. Lefigaro. Available online: https://www.lefigaro.fr/sciences/2018/06/26/01008-20180626ARTFIG00182-l-huile-de-palme-est-une-catastrophe-ecologique-mais-l-interdire-serait-pire-encore.php (accessed on 12 December 2022).
17. Lee, S.H.; Ashaari, Z.; Lum, W.C.; Halip, J.A.; Ang, A.F.; Tan, L.P.; Chin, K.L.; Tahir, P.M. Thermal treatment of wood using vegetable oils: A review. *Constr. Build. Mater.* **2018**, *181*, 408–419. [CrossRef]
18. Jensen, L.K.; Larsen, A.; M⊘lhave, L.; Hansen, M.K.; Knudsen, B. Health evaluation of Volatile Organic Compound (VOC) emissions from wood and wood-based materials. *Arch. Environ. Health* **2001**, *56*, 418–432. [CrossRef]
19. Coughlan, R.; Kilcawley, K.; Skibinska, I.; Moane, S.; Larkin, T. Analysis of volatile organic compounds in Irish rapeseed oils. *Curr. Res. Food Sci.* **2023**, *6*, 100417. [CrossRef]
20. Yang, H.; Gupta, S.K.; Dhital, N.B.; Wang, L.C.; Elumalai, S.P. Comparative investigation of coal- and oil-fired boilers based on emission factors, ozone and secondary organic aerosol formation potentials of VOCs. *J. Environ. Sci.* **2020**, *92*, 245–255. [CrossRef]

21. Wahab, R.; Sulaiman, M.S.; Samsi, H.W.; Ghani, R.S.M.; Mokhtar, N. The effectiveness of oil-heat treatment in the main chemical constitutes of planted 15-year-old acacia hybrid. *Asian J. Sci. Technol.* **2020**, *11*, 10692–10699.
22. Hill, C.; Altgen, M.; Rautkari, L. Thermal modification of wood-a review: Chemical changes and hygroscopicity. *J. Mater. Sci.* **2021**, *56*, 6581–6614. [CrossRef]
23. Dubey, M.K.; Pang, S.; Walker, J. Changes in chemistry, color, dimensional stability and fungal resistance of Pinus radiata D. Don wood with oil heat-treatment. *Holzforschung* **2011**, *65*, 49–57. [CrossRef]
24. Bessala, L.F.B.; Gao, J.; He, Z.; Wang, Z.; Yi, S. Effects of heat treatment on color, dimensional stability, hygroscopicity and chemical structure of Afrormosia and Newtonia wood: A comparative study of air and palm oil medium. *Polymers* **2023**, *15*, 774. [CrossRef] [PubMed]
25. Esteves, B.; Ayata, U.; Cruz-Lopes, L.; Brás, I.; Ferreira, J.; Domingos, I. Changes in the content and composition of the extractives in thermally modified tropical hardwoods. *Maderas Cienc. Y Tecnol.* **2022**, *24*, 22. [CrossRef]
26. Cech, P.; Tesarová, D. Comparison of VOC emissions from natural (untreated) Poplar wood and heat treated wood. *For. Wood Technol.* **2015**, *90*, 23–28.
27. Zhou, X.; Li, W.; Mabon, R.; Broadbelt, L.J. A critical review on hemicellulose pyrolysis. *Energy Technol.* **2016**, *4*, 1–29. [CrossRef]
28. Kacurakova, M.; Wellner, N.; Ebringerova, A.; Hromadkova, Z.; Wilson, R.H.; Belton, P.S. Characterisation of xylan-type polysaccharides and associated cell wall components by FT-IR and FT-Raman spectroscopies. *Food Hydrocoll.* **1999**, *13*, 35–41. [CrossRef]
29. Synytsya, A.; Novak, M. Structural analysis of glucans. *Ann. Transl. Med.* **2014**, *2*, 17.
30. Tan, L.; Dufresne, A.; Zhu, G.; Lin, N. Regioselective Modification at Reducing End Aldehydes of Cellulose Nanocrystals and Mercerization. *ACS Sustain. Chem. Eng.* **2023**, *11*, 4485–4497. [CrossRef]
31. Iiyama, K.; Wallis, A.F.A. Dissolution of wood with acetyl bromide solutions-reactions of lignin model Compounds. *J. Wood Chem. Technol.* **1990**, *10*, 39–58. [CrossRef]
32. Zeng, H.; Cao, D.; Qiu, Z.; Li, C. Palladium-catalyzed formal cross-coupling of diaryl ethers with amines: New tactic to slice 4-o-5 linkage in lignin models. *Angew. Chem.* **2018**, *130*, 3814–3819. [CrossRef]
33. Barclayl, R.C.; Cromwellg, R.; Hilbornj, W. Photochemistry of a model lignin compound. Spin trapping of primary products and properties of an oligomer. *Can. J. Chem.* **1994**, *72*, 35. [CrossRef]
34. Gu, X.; Cheng, K.; He, M.; Shi, Y.; Li, Z. La-modified SBA-15/H_2O_2 systems for the microwave assisted oxidation of organosolv beech wood lignin. *Maderas Cienc. Y Tecnol.* **2012**, *14*, 31–42. [CrossRef]
35. Ajayi, O.E.; Oladipupo, S.; Jegede, O.J. Comparative and synergistic influence of extracts of two tropical plants on the activity of the cowpea weevil, callosobruchus chinensis. *Med. Plant. Res.* **2018**, *8*, 60–73.
36. Risholm-Sundman, M.; Lundgren, M.; Vestin, E.; Herder, P. Emissions of acetic acid and other volatile organic compounds from different species of solid wood. *Holz Roh Werkst.* **1998**, *56*, 125–129. [CrossRef]
37. Čermák, P.; Rautkari, L.; Horáček, P.; Saake, B.; Rademacher, P.; Sablík, P. Analysis of Dimensional Stability of Thermally Modified Wood Affected by Re-Wetting Cycles. *BioResources* **2015**, *10*, 3242–3253. [CrossRef]
38. Nypelo, T.; Berke, B.; Spirk, S.; Sirvio¨, J.A. Review: Periodate oxidation of wood polysaccharides—Modulation of hierarchies. *Carbohydr. Polym.* **2021**, *252*, 117105. [CrossRef]
39. Wang, S.; Yuan, X.; Li, C.; Huang, Z.; Leng, L.; Zeng, G.; Li, H. Variation in the physical properties of wood pellets and emission of aldehyde/ketone under different storage conditions. *Fuel* **2016**, *183*, 314–321. [CrossRef]
40. Granström, K.M. Sawdust age affect aldehyde emissions in wood pellets. *Fuel* **2014**, *126*, 219–223. [CrossRef]
41. Rozas, R.; Aspée, N.; Negrete-Vergara, C.; Venegas-Yazigi, D.; Gutiérrez-Cutiño, M.; Moya, S.A.; Zúñiga, C.; Cantero-López, P.; Luengo, J.; Gonzalez, R.; et al. Solvent effects on the molecular structure of isolated lignins of Eucalyptus nitens wood and oxidative depolymerization to phenolic chemicals. *Polym. Degrad. Stab.* **2022**, *201*, 109973. [CrossRef]
42. Kopaczyk, J.M.; Warguła, J.; Jelonek, T. The variability of terpenes in conifers under developmental and environmental stimuli. *Environ. Exp. Bot.* **2020**, *180*, 104197. [CrossRef]
43. Giuffrè, A.M.; Capocasale, M.; Macrì, R.; Caracciolo, M.; Zappia, C.; Poiana, M. Volatile profiles of extra virgin olive oil, olive pomace oil, soybean oil and palm oil in different heating conditions. *LWT Food Sci. Technol.* **2020**, *117*, 108631. [CrossRef]
44. Chu, D.; Zhang, X.; Mu, J.; Avramidis, S.; Xue, L.; Li, Y. A greener approach to byproducts from the production of heat-treated poplar wood: Analysis of volatile organic compound emissions and antimicrobial activities of its condensate. *J. Clean. Prod.* **2019**, *213*, 521–527. [CrossRef]
45. Alzagameem, A.; Khaldi-Hansen, B.E.; Buchner, D.; Larkins, M.; Kamm, B.; Witzleben, S.; Schulze, M. lignicellulosic biomass as source for lignin-based environmentally benign antioxidants. *Molecules* **2018**, *23*, 2664. [CrossRef]
46. Salehi, A.M.; Trey, S.M.; Henriksson, G.; Johansson, M. Effect of Model Lignin Structures on the Oxidation of Unsaturated Fatty Acids. *Polym. Renew. Resour.* **2010**, *1*, 69–90.
47. Juita; Dlugogorski, B.Z.; Kennedy, E.M.; Mackie, J.C. Mechanism of formation of volatile organic compounds from oxidation of linseed oil. *Ind. Eng. Chem. Res.* **2012**, *51*, 5653–5661. [CrossRef]
48. Liu, P.; Liu, X.; Lai, F.; Ma, L.; Li, W.; Huang, P. The preparation of cyclopentadecanone and cyclopentadecanolide from *Malania oleifera Chum* oil. *bioRxiv* **2019**, 622423. [CrossRef]

49. Xu, J.; Zhang, Y.; Shen, Y.C.; Wang, Y.; Ma, Z.; Sun, W. New perspective on wood thermal modification: Relevance between the evolution of chemical structure and physical-mechanical properties, and online analysis of release of VOCs. *Polymers* **2019**, *11*, 1145. [CrossRef]
50. Faix, O.; Bremer, J.; Schmidt, O.; Stevanovic, J.T. Monitoring of chemical changes in white-rot degraded beech wood by pyrolysis-gas chromatography and Fourier-transform infrared spectroscopy. *J. Anal. Appl. Pyrolysis* **1991**, *21*, 147–162. [CrossRef]
51. Hussain, M.A.; Nathar, V.N.; Mir, J.I. Gas Chromatography-Mass Spectrometry (GC-MS) analysis in callus extracts of *Ruta graveolens* L. *World J. Pharm. Res.* **2017**, *6*, 1195–1210.
52. Huang, Y.; Zhang, Y.; Qi, Y.; Yu, Y.; Yu, W. Identification of odorous constituents of bamboo during thermal treatment. *Constr. Build. Mater.* **2019**, *203*, 104–110. [CrossRef]
53. Li, T.; Li, G.; Li, J.; Li, X.; Li, M.; Li, Y. HSSPME and GC-MS for the analysis of odorous constituents from heat treated rubber wood and the chemical change of heat treated rubber wood by xps analysis. *Wood Sci. Technol.* **2021**, *55*, 361–378. [CrossRef]