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Oil heat-treatment of *Eucalyptus nitens* (H.Deane & Maiden) Maiden timber

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Abstract

Background: Thermal modification of nondurable *Eucalyptus nitens* timber was reported to result in excessive checking and only marginally improved durability when heat treating in steam or atmospheric environments. This study investigated if oil heat-treatment of *E. nitens* above 210°C was able to overcome previously reported difficulties.

Methods: *Eucalyptus nitens* clears were oil heat-treated to 210°C, 220°C and 230°C and assessed for density, stiffness, strength, colour and decay resistance.

Results: Oil heat-treated *E. nitens* samples showed mass loss matching the highest durability class when tested against the brown-rot *Rhodonia placenta* (Fr.) Niemelä, K.H.Larss. & Schigel and the white-rot *Trametes versicolor* (L.) Lloyd, matching Durability Class-2 rated *Eucalyptus muelleriana* A.W.Howitt heartwood. Oil heat-treated *E. nitens* samples outperformed *Pinus radiata* treated with chromated copper arsenate (CCA) to Hazard Class (H3) grade when tested for the brown-rot *R. placenta*. While oil heat-treatment reduced mean stiffness (MoE) and strength (MoR), the resulting material exceeded characteristic SG8 grade values. No checking was observed in the oil heat-treated *E. nitens* boards. Letting samples cool outside the oil bath limited uptake of oil to less than 4 mm in depth. The planed product became darker the higher the oil heat-treatment temperature.

Conclusions: Oil heat-treatment above 210°C has the potential to refine *E. nitens* timber, avoiding excessive degrade and providing decay resistance.

Keywords: Checking; colour; decay; durability; mass loss; shining gum; strength; thermal modification; nitens; oil

Introduction

Eucalyptus nitens (H.Deane & Maiden) Maiden is a fast-growing commercial plantation species, which produces a light coloured and non-durable timber (Standards Australia 2022). It is primarily grown for wood fibre. Use for higher-value solid wood products is possible but challenges with knots, drying collapse and high growth strains need to be overcome (Nolan et al. 2005; Washusen 2013). Outdoor timber is a significant market segment accounting for a fifth to a half of timber consumption in Australia (Dunn 2011). Technical options to enhance the durability of non-durable eucalypts have been recently reviewed (Wood et al. 2020), among them is thermal modification (Ghani & Lee 2021).

Thermal modification, typically in an oxygen deficient environment, is a commercial environmentally friendly process to make wood more durable, darker, and a more dimensionally stable product at the cost of lower strength. Comprehensive reviews on thermal wood modification have been published (Candelier et al. 2016; Esteves & Pereira 2009; Hill 2006; Hill et al. 2021; Lee et al. 2018; Zelinka et al. 2022). While the magnitude of the

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thermal treatment effect is species specific, in general, higher temperature and longer treatment time increase these effects.

Thermal modification does not provide the same level of decay resistance as can be achieved with chemical treatments and is unsuitable for in-ground conditions (Candelier et al. 2016; Welzbacher & Rapp 2007; Zelinka et al. 2022). But, thermally modified timber is commercially produced for non-structural above-ground applications such as decking or cladding. Higher temperatures in particular between 200 and 240°C result in increased decay resistance, when normalised for mass loss during thermal treatment (i.e. treatment time) (Candelier et al. 2016). To obtain the same decay resistance, hardwoods require higher mass loss than softwoods when normalised for temperature (Chaouch 2011), impacting negatively on mechanical properties.

Several heat treatment processes have been developed (Hill et al. 2021). The oil heat-treatment process, where timber is thermally treated in a hot oil bath (Lee et al. 2018), is less common but had been commercialised (Rapp & Sailer 2001). It was reported to provide a more consistent appearance and to have less impact on strength while achieving better durability compared to gas-phase heat treatment processes (as summarised by Lee et al. (2018)). Less surface checking was also reported (Sailer et al. 2000). The process can be conducted with and without oil impregnation of the wood. Oil does not enter the interior of the wood during the heat treatment, but a negative pressure develops inside the cell lumens if the wood is cooled while submerged in the oil bath, facilitating impregnation (Dubey et al. 2012; Karlsson et al. 2011; Rapp & Sailer 2001).

Little and inconsistent information is available on thermal treatment of *E. nitens* in atmospheric or steam environments. To the best of our knowledge, oil heat-treatment has not been tested for this species. Studies in New Zealand have reported slightly improved decay resistance when treated at 210°C but not matching the performance of timber treated with preservative for above-ground outdoor use (Sargent et al. 2019; Sargent & Dunningham 2018). Further, uneconomic levels of downgrade due to checking were found. Studies on thermal modification of Chilean and Spanish *E. nitens* timber up to 230°C did not report problems with checking in the products, but focused on investigating disintegration of the wood tissue by microscopy (Wentzel, Brischke, et al. 2019; Wentzel, Fleckenstein, et al. 2019; Wentzel, González-Prieto, et al. 2019). The authors suggested that *E. nitens* should be suitable for decking when thermally treated at 200°C, having similar mechanical properties to commonly used species and good abrasion resistance. However, decay resistance of the material was not tested. Thermal modification of a range of other eucalyptus species has been studied (Table 1 & Table S1). What can be concluded from the literature is that *E. nitens*, in principle, does not behave differently to other eucalypts when thermally modified. Checking has not been reported as a major problem when heat treating eucalypts.

The purpose of this study was to investigate if oil-heat treatment at higher temperatures has the potential to produce an above-ground durable product from plantation-grown *E. nitens* in acceptable yields, i.e. with a limited amount of checking.

Methods

Materials

Four 1.2 m long air-dried and rough sawn *E. nitens* boards 28 mm thick and 80 mm wide were cut into four ~280 mm long samples. The samples appeared to be heartwood. Each board came from a different locally grown tree and was supplied by Speciality Timber Solutions, Sefton, New Zealand. A sample from each board was used in each of the three temperature treatments (~210°C, ~220°C and ~230°C) as well as the control group. Additional, two shorter samples were cut from each board to determine moisture content (MC) after equilibration before and after oil heat-treatment. All samples were conditioned to constant weight at 20°C and 65% relative humidity (RH).

Oil heat-treatment

Conditioned wood specimens were immersed in recycled canola oil. Oil heat-treatment (OHT) continued for 3 h once the sample core reached the desired treatment temperature of ~210°C, ~220°C or ~230°C, respectively. The temperature of the oil bath (24 (w) x 30 (l) x 19 (d) cm) was monitored with an IR thermometer, Amprobe. The core temperature of the wood samples was monitored on a sacrificial sample with a temperature sensor (ATP Thermometer DT-610B) inserted into a 4 mm hole and were sealed with high temperature grease (Inox-mx6). After treatment, the samples were removed from the oil bath and allowed to cool and drip off oil on an incline. The specimens were then reconditioned at 20°C and 65% RH.

Density, mass loss, volumetric shrinkage and moisture content

Length, width and thickness of the samples was measured at opposing ends with a calliper and the measurements were averaged. Samples were weighed. Volume (average length x average width x average thickness) and density (volume / mass) were calculated. Moisture content (MC) was defined as the weight difference of the sampled before and after drying at 103°C in relation to the dry weight. Oven-dry mass of the specimens was calculated from their mass conditioned at 20°C and 65% RH and the MC of the matching MC sample. Percentage changes in mass, density, dimensions and volume at 20°C and 65% RH caused by oil heat-treatment were defined as:

OHT effect (%) = (Measurement before OHT – Measurement after OHT) / Measurement before OHT

TABLE 1: Summary of studies on durability of thermally modified eucalyptus timbers

Material	Temperature (°C)	Process	Durability test	Finding	Reference
Decay					
E. nitens	185, 210 173 ~210	Atmospheric Steam Steam	'Sutter durability screening lab test', fungus cellar stakelets	Heat treatment at 185°C did not enhance durability, while some improvement was observed for samples heated to 210°C. These still did not match *Pinus radiata* D.Don treated with chromated copper arsenate (CCA) to H3.2 grade. Samples steamed at ~210°C performed like those heated to 210°C under atmospheric conditions	Sargent et al. 2019
Eucalyptus globulus Labill.	180	Inert atmosphere (sand bath?)	EN113	Mass loss *Gloeophyllum trabeum* (Pers.) Murrill (BR): 0.06-0.08% (very durable according to EN350)	González-Prieto & Touza 2009
E. globulus, Eucalyptus botryoides SM. (6-year-old)	210	Sand bath	EN 252	Field test showed no suitability for in-ground use for thermally modified *E. globulus*. Thermal treatment might have potential for above-ground use, which was not tested	Knapic et al. 2018
Eucalyptus grandis W.Hill ex Maiden (6-year old)	140, 160, 180, 200, 220	Atmospheric	ASTM D2017	Mass loss (%) (control, 140, 160, 180, 200, 220) *Pycnoporus sanguineus* (L.) Murrill (WR): 34.32, 33.19, 32.57, 28.95, 23.81, 6.05	Calonego et al. 2012; Calonego et al. 2010
	180, 200, 220			Mass loss (%) (control, 180, 200, 220) *G. trabeum* (BR): 50.33, 36.12, 23.51, 15.10	Calonego et al. 2013
E. grandis (23-year old), heartwood and sapwood	200, 215, 230	Atmospheric	Field test	Thermal modification seemed to improve decay resistance for sapwood and termite resistance for heartwood	Trevisan et al. 2014
E. grandis (25-years old)	160 130 + 160	Atmospheric Steam / Atmospheric	IBAMA (LPF) / ASTM D2017	No (or unfavourable) effect of heat treatments on mass loss by *G. trabeum* (BR) and *T. versicolor* (WR)	Modes et al. 2017
E. grandis (7-year old trees)	160	Steam	ASTM D1413	Thermal treatment had no effect on decay Mass loss (%) (control, 160): *R. placenta* (BR): 42.29, 45.14 *T. versicolor* (WR): 16.54, 22.69	Brito et al. 2023
E. grandis	140, 160	Saturated steam	Field test	Mass loss (%) (control, 140, 160): 8.24, 9.44, 4.15 Thermal modification did not affect dynamic MoE loss due to decay	Carvalho et al. 2019; Juizo et al. 2019
E. grandis	140, 160	Saturated steam	ASTM D1413	Mass loss (%) (control, 140, 160) *Lentinula edodes* (Berk.) Pegler (WR): 10.58, 6.93, 4.67 *Pleurotus djamor* (Rumph. ex Fr.) Boedijn (WR): 4.67, 2.65, 5.37 Note: these fungi are edible and known as shiitake and pink oyster mushroom	Bellon et al. 2020
E. grandis (heartwood)	160, 180, 200	Vacuum	EN 113	Except for 160°C thermally treated wood met the 'very durable' requirement when tested against *T. versicolor* (WR) and *P. sanguineus* (WR)	Cantera et al. 2022
Eucalyptus tereticornis Sm., *Corymbia citriodora* (Hook.) K.D.Hill & L.A.S.Johnson (~60-year old)	120 180 120 + 180	Steam Atmospheric Steam / Atmospheric	ASTM 2017	Heat treatment had some effect on *C. citriodora* (class 2 AS5604) but not *E. tereticornis* (class 1 AS5604) timber. Mass loss (%) (control, 120, 180, 120+180). *T. versicolor* (WR): 2.06, 0.84, 0.18, 0.06. *Ganoderma applanatum* (Pers.) Pat. (WR): 3.48, 1.76, 0.52, 0.00	Lazarotto et al. 2016

TABLE 1: *continued.*

Material	Temperature (°C)	Process	Durability test	Finding	Reference
Decay					
C. citodora (20-year old)	100, 160, 180, 200, 220, 240	Nitrogen	ASTM D1413	Mass loss was low (<8%) for all tests samples. Temperatures of 200°C and above promoted decay resistance for all tested fungi Mass loss (%) (100, 160, 180, 200, 220, 240) *T. versicolor* (WR): 2.38, 6.35, 7.7, 1.90, 0.65, 0.45; *G. trabeum* (BR): 2.19, 4.44, 4.68, 2.23, 0.77, 0.22; *Neolentinus lepideus* (Fr.) Redhead & Ginns (BR): 2.03, 4.84, 4.48, 1.59, 0.71, 0.41; *R. placenta* (BR): 2.41, 3.71, 2.76, 1.73, 0.57, 0.15)	Paes et al. 2021
Eucalyptus bosistoana F.Muell (50-year old sapwood)	<150	Surface contact hot plate	EN 113 ASTM D3345	'Charring' resulted very dark surfaces (ie should have experienced > 150°C). Durability of sapwood was increased to moderately durable for *T. versicolor* (WR), durable for *Irpex lacteus* (Fr.) Fr. (WR), very durable for *Coniophora puteana* (Schumach.) P. Karst. (BR), and durable for *Tyromyces palustris* (Berk. & M.A.Curtis) Murrill (BR)	Soytürk et al. 2023
Termites					
Eucalyptus urophylla S.T.Blake (chips from 7-year old trees)	180, 220, 260	Atmospheric	IPT 1157	*Cryptotermes brevis* (Walker) Mass loss (%) (control, 180, 220, 260) No choice test: 1.69, 0.68, 0.63, 0.33 Preference test: 5.52, 1.30, 0.02, 0.04	de Castro et al. 2019
E. grandis (21-years old)	120, 140, 160, 180, 200	Atmospheric	IPT 1157	*C. brevis* Mass loss (%) (control, 120, 140, 160, 180, 200): 2.70, 2.44, 2.40, 2.60, 2.20, 2.10	Pessoa et al. 2006
E. grandis (18-years old)	140, 160, 180	Saturated steam	IPT 1157	No statistically significant effect on termite resistance. *C. brevis* Mass loss (%) (control, 140, 160, 180): 0.82, 0.58, 0.94, 1.05	Batista et al. 2016
E. grandis (7-year old trees)	160	Steam	ASTM D3345	Thermal treatment had some effect on termites Mass loss (%) (control, 160): *Nasutitermes corniger* (Motschulsky): 8.29, 6.67 *C. brevis*: 1.85, 1.41	Brito et al. 2023
C. citriodora (18 to 20-years old)	160, 180, 200, 220, 240	Nitrogen	Food preference test & ASTM 3345 no choice test	Thermal treatment above 200°C improved termite resistance, while termite resistance was decreased at lower treatment temperatures. *N. corniger* Mass loss (%) (control, 160, 180, 200, 220, 240) Preference test: 2.04, 14.78, 6.35, 2.87, 0.20, 0.10 No choice test: 2.24, 3.20, 2.10, 1.92, 0.80, 0.41	Paes et al. 2015; Paes et al. 2016
E. bosistoana (50-year old sapwood)	<150	Surface contact hot plate	ASTM D3345	Termite (*Reticukitermes flavipes* Kollar) resistance increased from very poorly resistant to poorly resistant.	Soytürk et al. 2023

Colour

Equilibrated oil heat-treated samples and untreated controls were planed and subsequently scanned at 600 DPI. Colour parameters were extracted from the digital images (Plata & Delos Santos 18/05/2022 - 20/05/2022) using the histogram function in ImageJ (Schneider et al. 2012), extracting R, G and B mean values for an oil spot free area of at least 10 Mpixels. RGB mean values were converted into CIE L, a and b values using an online converter (http://colormine.org/convert/rgb-to-lab). The total colour change ΔE was calculated as:

$$\Delta E = \sqrt{(\Delta L^2 + \Delta a^2 + \Delta b^2)}$$

Determination of physical and mechanical properties

After the colour assessments, each sample was ripped into three 20 mm x 20 mm sticks. The outer two samples were used for 3-point bending tests, which were conducted with a universal testing machine using a support span of 242 mm at a rate of 1.33 mm/min similar to ASTM (2022).

Assessment of decay resistance

Specimens were cut from the central strip (see above) of the *E. nitens*, obtaining test specimens measuring 20 × 20 × 10 mm (with 10 mm along the grain direction) following (AWPC 2015). Equally dimensioned specimens were prepared from *E. nitens* sapwood, *Eucalyptus muelleriana* A.W.Howitt heartwood and *Pinus radiata* treated with chromated copper arsenate (CCA) to H3.2 grade (Figures S1, S2 and S3). Specimens were conditioned at 20°C and 65% RH. Some spare blocks were used to determine moisture content (MC) for calculating the theoretical oven-dry mass, in accordance with EN 350-1 and EN 113.

The mass loss test followed EN 350-1 (European Committee for Standardization 1994) and EN 113 (European Committee for Standardization1996), with modifications based on ASTM (2005), Australasian Wood Preservative Committee (2015) and Cookson (unpublished data). The white-rot *Trametes versicolor* (L.) Lloyd and the brown-rot *Rhodonia placenta* (Fr.) Niemelä, K.H.Larss. & Schigel were selected as decay fungi. Test blocks were sterilised using ethylene oxide gas before being exposed to the decay fungi growing on malt extract agar. The sterilised specimens were positioned with the end-grain on a sterilised stainless-steel mesh placed on top of the established mycelium. The trays were incubated at 25˚C and 75% RH in a growth cabinet. The samples were removed after 12 weeks, gently wiped to remove excess surface mycelium, and oven-dried at 103°C until they reached a constant mass. The final weight was recorded to determine mass loss (*ML*):

$$ML\ (\%) = ((M_t - M_f)/\ M_t) \times 100$$

Where M_t and M_f are the initial (theoretical oven-dry mass) and final mass of the sample, respectively. Sapwood specimens of *E. nitens* served as reference species to verify the vitality of the fungal cultures.

Data analysis

Statistical tests (ANOVA, Tukey HSD) were performed in R (R Core Team 2022). Non-significant variables ($p > 0.05$) were removed from the models. Replicate measurements per sample were treated as nested within each board.

Results and Discussion

The average temperatures in the core of the wood samples during the treatment time was 213, 223 and 235°C, respectively (Table 2). Treatment time at the desired temperature was between 3 and 3.5 hours (Table 2), with an additional heating-up time varying between 50 and 70 minutes (Figures S4, S5 and S6). This was at the upper end of typical thermal timber treatment temperatures (160-240°C) (Hill et al. 2021; Zelinka et al. 2022).

TABLE 2: Conditions for oil heat-treatment of *E. nitens*

Treatment	Temperature (°C)	Treatment time (h)	Oil loss (g)
Set 1	213	3	~128
Set 2	223	3.5	~126
Set 3	235	3	~194

Increasing the temperature of the oil heat-treatment of the *E. nitens* boards from 213°C to 235°C increased the loss of cell wall material from 6.5% to 13.1%

TABLE 3: Mean properties for oil heat-treated *E. nitens* (standard deviation in parenthesis). Superscript letters indicate TukeyHSD 95% confidence levels. nd = not determinable; OD: oven dry. [5th percentile MoR values in brackets]

	n	Control	OHT at ~210°C	OHT at ~220°C	OHT at ~230°C
$MC_{20°C;\ 65\%}$ (%)	4	11.8 (0.3)	4.0 (nd)	4.3 (nd)	4.3 (nd)
$Density_{20°C;\ 65\%}$ (kg/m^3)	4	593.6 (21.9)^a	564.7 (27.7)^b	535.8 (24.7)^c	522.7 (23.4)^c
Mass $loss_{OD}$ (%)	4	nd	6.5 (0.3)^a	10.9 (0.4)^b	13.1 (0.4)^c
Volume $loss_{20°C;\ 65\%}$ (%)	4	nd	6.0 (1.3)^a	6.9 (1.9)^{ab}	8.3 (1.3)^b
MoE (GPa)	8	11.6 (0.6)^a	11.2 (1.6)^a	10.9 (1.7)^{ab}	9.3 (1.7)^b
MoR (MPa)	8	106.2 (9.6)^a [90.5]	64.1 (18.2)^b [40.2]	56.0 (22.7)^b [28.3]	43.9 (18.2)^b [23.8]

(Table 3). The oil heat-treatment had a profound effect on the equilibrium moisture content at 65% relative humidity and 20°C, reducing form 11.8% for the untreated *E. nitens* controls to ~4% for the oil heat-treated samples (Table 3). The reduced equilibrium moisture content of the oil heat-treated samples was consistent with the reduced dimensions, expressed as volume loss in Table 3. The reduced dimensions imply the need to cut larger boards from the green logs to reach a target product dimension compared to conventional sawn timber products. Oil heat-treatment significantly reduced the density of the *E. nitens* boards at equilibrium conditions (65% relative humidity and 20°C) from 590 kg/m^3 for the control to 520 kg/m^3 when oil heat-treated at 230°C (Table 3). While oil heat-treatment did roughly halve the strength (MoR) of the timber, stiffness (MoE) was only significantly affected by the most sever thermal treatment, reducing it by ~20%. Except for MoE, more variation was associated with thermal treatment temperature than between boards. All observed changes were consistent with literature on thermal timber treatment (Hill 2006; Lee et al. 2018; Zelinka et al. 2022). The mean stiffness (MoE 9.3 to 11.2 GPa) and 5th percentile strength (MoR 23.8 to 40.2 MPa) of the oil heat-treated *E. nitens* (Table 3) compared favourably with characteristic design values for SG 8 structural timber (MoE 8 GPa; MoR 14 MPa) (Standards New Zealand & Standards Australia 2022), which is recommended for decking material (BRANZ 2013). However, two things need to be noted. Firstly, in contrast to typical SG8 timber the samples in this study were clear wood without defects for which higher values are to be expected. And secondly, the characteristic strength for SG8 is based on the 5th percentile rather than the mean (Standards New Zealand 2004), which were between 23.8 and 40.2 MPa for the oil heat-treated timber (Table 3).

Colour and checking

The oil heat-treatment had profound effects on the colour of the *E. nitens* boards (Figure S7). Boards became significantly darker than the control and the samples treated at 210°C were lighter coloured than those treated at higher temperature (Table 4). Oil heat-treatment temperature also significantly increased the yellowness (CIE b) of the boards. While the redness (CIE a) of the boards was significantly different between the controls and the oil heat-treated samples, the effect differed in sign depending on the treatment temperature. The overall colour change was also significantly different between all oil heat-treatment temperatures. These colour changes were as expected for heat treated wood (Griebeler, Tondi, et al. 2018; Lee et al. 2018). It should be noted that colour variation between trees is significant and under genetic control (Vanclay et al. 2008). Heat treatment reduces colour variation (Griebeler, de Matos, et al. 2018), which can be improved further by pre-grading (Griebeler, Tondi, et al. 2018).

Removing the wood from the hot oil bath for cooling prevents larger uptake of oil into the material (Dubey et al. 2012). However, oil penetrated into the surface layers of the *E. nitens* boards. Due to different board dimensions, planing to the targeted 20 mm thickness removed between 8 and 4.5 mm of material from one rough sawn surface. For some boards this was not enough to remove all oil-soaked material and the samples showed spots of oil stain (Figure S7). Oil-soaked material might affect appearance when used with clear finishes. If the product is stained, as is commonly recommended for decking, this should become invisible. Indeed commercially heat treated, but not oil heat-treated, decking is sold with oil coating already applied. The remaining trace amounts should not significantly impact absorption of an oil coating. Planing has been recommended of oil heat-treated timber before gluing (Rapp & Sailer 2001). Good results were obtained for coating oil heat-treated timber with certain systems (Lee et al. 2018; Rapp & Sailer 2001).

In contrast to previous reports that thermal modification of *E. nitens* is associated with extensive checking (Sargent 2019; Sargent et al. 2017), no checking was observed in this study (Figure S7).

Decay resistance

After 12 weeks of exposure to the white-rot *T. versicolor*, control samples of untreated *E. nitens* sapwood lost over 50% of their mass, indicating that the test was valid (Table 5). Oil heat-treated samples lost less than 2% of their mass, performing as well as H3 CCA-treated *P. radiata* and *E. muelleriana* heartwood which is listed having an above-ground Durability Class 2 (Bootle 2005).

The brown-rot *R. placenta* caused less than 3% mass loss in the eucalyptus specimens, while the H3 CCA-treated *P. radiata* lost 15% after 12 weeks exposure (Table 5). The more severe degradation of H3 CCA-treated *P. radiata* compared to the hardwood samples was consistent with the known preference of this fungus for softwoods (European Committee for Standardization 1996).

TABLE 4: Mean (n = 4) colour characteristics for oil heat-treated *E. nitens* (standard deviation in parenthesis). Superscript letters indicate TukeyHSD 95% confidence levels. nd = not determinable, ΔE overall colour change.

Parameter	Control	OHT at ~210°C	OHT at ~220°C	OHT at ~230°C
CIE L (brightness)	76.9 (0.6)^a	25.1 (0.9)^b	20.3 (0.5)^c	18.7 (1.6)^c
CIE a (red-green)	3.3 (0.2)^b	3.8 (0.1)^a	2.5 (0.1)^c	1.9 (0.2)^d
CIE b (yellow-blue)	17.0 (0.7)^a	12.3 (0.2)^b	9.0 (0.4)^c	7.4 (0.8)^d
ΔE (overall colour change)	nd	52.0 (1.0)^a	57.1 (0.4)^b	59.0 (2.0)^b

TABLE 5: Mean mass loss (%) by the white rot *T. versicolor* and the brown rot *R. placenta* of oil heat-treated *E. nitens* and selected controls (standard deviation in parenthesis). Superscript letters indicate TukeyHSD 95% confidence levels. n: number of samples, HW: heartwood; SW: sapwood.; H3 CCA: treated with chromated copper arsenate to H3 grade.

	***E. nitens* HW**	***E. nitens* HW**	***E. nitens* HW**	***E. nitens* HW**	***E. mulleriana* HW**	***E. nitens* SW**	**H3 CCA *Pinus radiata***
	OHT Control	**OHT ~210°C**	**OHT ~220°C**	**OHT ~230°C**			
n	20	20	20	20	5	5	5
Mass loss (%) *T. versicolor*	27.7 (11.5)[a]	1.7 (1.5)[b]	0.6 (1.7)[b]	0.8 (2.0)[b]	0.1 (0.3)[b]	62 (17.5)[c]	0.1 (0.3)[b]
Mass loss (%) *R. placenta*	0.9 (2.6)[a]	0.9 (2.5)[a]	1.1 (2.2)[a]	0.7 (2.1)[a]	-0.4 (0.8)[a]	1.8 (3.4)[a]	14.9 (12.9)[b]

No statistical difference in mass loss between the three oil-heat treatment temperatures was found for either fungus (Table 5). This was expected as the mildest oil-heat treatment at 213°C already rendered the material indigestible for the tested fungi. This observation was also consistent with literature, reporting best durability of eucalypt timbers when treated above 200°C (Carvalho et al. 2019; Juizo et al. 2019; Paes et al. 2021). Specifically, mass loss of less than 2% against the test fungi *T. versicolor* and *R. placenta* was reported for eucalypt heat treated timber at or above 200°C (Cantera et al. 2022; Paes et al. 2021). Higher mass losses against the two fungi were reported for eucalypt timber heat treated at 160°C (Brito et al. 2023; Modes et al. 2017).

Durability classification according to a standard such as EN 113 or ASTM 2017 requires testing against more fungi. However, for the two tested fungi, oil heat-treated *E. nitens* samples were at least on par with H3 CCA treated *P. radiata* and matched that of above-ground durable *E. muelleriana* heartwood.

Conclusions

These findings indicate potential to use oil-heat treated *E. nitens* for non-structural, above-ground applications such as decking and cladding. Previous reports that heat treating *E. nitens* results in excessive checking could not be confirmed. Decay resistance against *T. versicolor* and *R. placenta* were at least on par with H3 treated *Pinus radiata* and above-ground Class 2 durable *E. muelleriana* heartwood. It should be noted that mean MoE and mean MoR exceed characteristic values for SG8. Further investigation will be needed to determine if oil heat-treated *E. nitens* is an economically viable process. However, the recent commissioning of an oil heat-treatment plant in Sefton, New Zealand, indicates a favourable business case.

Competing interests

JRF is director of John Fairweather Speciality Timber Solutions Limited. CMA and FAA declare that they have no competing interests.

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Authors' contributions

CMA conceived the study, conducted experiments, analysed the data and drafted the manuscript. FAA conducted and analysed the decay tests, and drafted the decay section of the manuscript. JRF conceived the study, engineered the oil heat-treatment and supplied the timbers. All authors revised and approved the submission.

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Supplemental Information

TABLE S1: Summary of studies on physical properties of thermally modified eucalyptus timbers.

Material	Temperature (°C)	Process	Finding	Reference
E. nitens (19 year-old)	160, 180, 200, 210, 220, 230 150, 160, 170	Atmospheric Steam	No difference in mechanical and anatomical properties between the processes. But steam process caused stronger modification of wood chemistry. Indication that chemical changes were associated with brittle wood	Wentzel, Brischke et al. 2019; Wentzel, Fleckenstein et al. 2019
E. nitens (16 & 19 year-old)	185, 200, 215	Atmospheric	Similar high abrasion resistance as commonly used species	Wentzel, González-Prieto et al. 2019
E. nitens	160, 185, 210 173 ~210	Atmospheric Steam Steam	After 7 months exposure to sunlight, the colour of the heat modified boards and the control were similar. Thermal modification did not significantly change MoE but halved MoR at 210°C. Heat treatment in atmospheric conditions caused unacceptable levels of checking. Less checking in steamed wood	Sargent et al. 2017; Sargent & Dunningham 2018
E. nitens, Tasmanian oak (veneers)	200	Hot press	Loss in density and mechanical performance due to thermal treatment can be counteracted by densification	Balasso et al. 2020
E. grandis decking	160	Saturated steam	Anisotropy of wood not affected by heat treatment	Bonfatti Júnior et al. 2022
E. grandis	140, 180, 220 140, 180, 220 140, 180, 220	Vacuum Nitrogen Vacuum + nitrogen	More changes happen to wood when treated under nitrogen compared to vacuum	de Oliveira Araújo et al. 2012; Soratto et al. 2020
E. grandis (30year-old)	180	Atmospheric	Thermal modification increased calorific value; effect of thermal modification more pronounced for mature wood compared to juvenile wood.	Calonego et al. 2014; Calonego et al. 2016
E. grandis (25 year old)	160 130 + 160	Atmospheric Steam / Atmospheric	Better modification was achieved by sequential steam and atmospheric treatments compared to simple atmospheric treatment	Modes et al. 2013
E. grandis (23 year-old)	180, 200, 215, 230	Atmospheric	Temperature as well as treatment duration promote physical changes in the wood	Garcia et al. 2012
E. grandis (20 year-old, juvenile and mature wood)	120, 150, 180	Atmospheric	Mature wood lost more mass, but heat treatments affected mechanical propertied and shrinkage more for juvenile wood	Bal & Bektaş 2012, 2013
E. grandis (19 year-old)	140, 160, 180	Saturated steam	No quantitative changes in wood anatomy were detected in any cell type. Radial swelling reduced less than tangential and volumetric swelling	Batista et al. 2015; Batista et al. 2018
E. grandis (18 year-old sapwood)	140, 160, 180, 200	Nitrogen	Planing quality improved with heat treatment temperature, while sanded surfaces became rougher. Adhesion of coating decreased above 160°C. 160°C yielded optimum colour stability and colour change increased from 180°C	de Moura & Brito 2011; de Moura et al. 2011; de Moura et al. 2013
E. grandis (18 year-old)	140, 160, 180	Saturated steam	Colour becomes more consistent when treated at 180°C	Griebeler et al. 2018a
E. grandis (15 year-old)	140, 170, 200, 230	Atmospheric	Temperature was more effective than time to change the colour and chemical composition of timber. Random sampling is appropriate for evaluating heat treated wood as parameters had a low coefficient of variation	Zanuncio, Farias et al. 2014; Zanuncio, Motta et al. 2014; Zanuncio, Nobre et al. 2014

TABLE S1: *continued*

Material	Temperature (°C)	Process	Finding	Reference
E. grandis (9 & 10 year-old)	155, 165, 175, 185	Steam	Regression model to predict mechanical properties from thermal treatment temperature. Weak correlation for toughness	Oliveira et al. 2021; Oliveira et al. 2022
E. grandis (7 year old trees)	160	Steam	Comparable to thermally modified 15-year-old teak	Brito et al. 2023
E. grandis (17 year-old)	180, 200, 220, 240	Atmospheric	Treatment duration influenced weight loss, while the temperature influenced all studied properties. More significant modifications with treatments above 200°C, where treatment duration became also more relevant	De Cademartori et al. 2012; de Cademartori et al. 2013
E. grandis (17 year-old)	180, 200, 220, 240 127 + (180, 200, 220, 240)	Atmospheric Steam + Atmospheric	Pre-steaming does not affect wood properties when subsequently treated above 200°C. Strength remained acceptable even at high temperature.	de Cademartori et al. 2015
E. grandis x *E. urophylla* (clone GLGU9)	150, 170, 190, 200, 210	Palm oil	While treatment temperature had a larger effect on dimensional stability, treatment duration and the interaction between temperature and treatment duration were still significant (P = 0.01)	Cao et al. 2023
E. grandis x *E. urophylla*	180, 200, 220	Nitrogen	Numerical model to monitor heat treatment process from temperature measurements for quality control	Zhao et al. 2017
E. grandis x *E. urophylla* (7 year-old)	165, 185, 205	Atmospheric	Colour of teak could be matched at 185°C	Lu et al. 2022
E. urograndis clones (8.5 year-old)	140, 160, 180, 200, 220	Atmospheric	No effect of clone on tested properties of heat-treated timber	Barreiros et al. 2023
E. grandis x *E. urophylla* (9 year-old clones)	120, 180	Atmospheric Steam	Atmospheric heat treatment resulted in most consistent material properties, suggesting easier quality control	Batista et al. 2022
E. grandis x *E. urophylla* (10 year-old)	160, 180, 200, 220	Steam	Heat treatment decreased crystallinity of cellulose and increased distance between the crystal planes. While the amount of carbonyl groups was unaffected by heat treatment methyl groups decreased with temperature. Aromatic groups showed a non-liner behaviour with temperature.	Cheng et al. 2017
E. grandis x *E. urophylla* (14 year-old clones)	185, 200	Atmospheric	Heat treated decking changed colour less due to weathering than untreated controls	Andrade et al. 2024
E. grandis, E. urophylla and *E. grandis* x *E. urophylla* (10 year-old clones)	200	Atmospheric	Heat treated wood met mechanical wear requirements for flooring	Juizo et al. 2021
E. urophylla (8 year-old)	150, 170, 190	Atmospheric	Heat treatment at 150°C improved dimensional stability and colour uniformity but without reducing mechanical strength	Yang & Jin 2021
E. globulus	180	Atmospheric	Little difference in flat sawn and quarter sawn bending strength	Santos 2000

TABLE S1: *continued*

Material	Temperature (°C)	Process	Finding	Reference
E. globulus	190, 200, 210 190	Steam Atmospheric	Improvements in dimensional stability can be obtained for a 3–4% mass loss without impairing mechanical performance. With increasing temperature, hemicelluloses degraded first (arabinose and xylose), lignin at a slower rate and cellulose was only slightly affected. Almost all original extractives disappeared, and new compounds formed. The atmospheric process resulted in more oxidized extractives	Esteves et al. 2007; Esteves, Graca, et al. 2008
E. globulus	190, 210 170, 180	Steam Atmospheric	Wood colour changed more in atmospheric than steam heat treatment	Esteves, Velez Marques, et al. 2008; Esteves et al. 2013
E. globulus (25 to 35 years old)	140, 160, 180, 200, 220	Atmospheric	Pre-grading for colour can produce a more homogeneous product after thermal treatment	Griebeler et al. 2018
E. pellita (25 to 35 year-old)	140, 160, 180, 200, 220, 240	Vacuum	Heat treatment temperature reduced hydrogen and increased carbon content. Hemicellulose degradation and lignin condensation were observed. Equilibrium moisture content and sorption hysteresis decreased with treatment temperature	Sun et al. 2017
E. pellita (8 year- old)	170, 200	Atmospheric	Removal of polar extractives did not change the colour of the thermally treated timber	Zanuncio et al. 2016
E. camaldulensis	120, 150, 180	Atmospheric	Radial Janka hardness reduced by up to 45%. Tangential and end-grain hardness were less affected	Unsal et al. 2003
E. cloeziana (17 year-old, fast-growth)	180, 200, 220, 240 127 + (180, 200, 220, 240)	Atmospheric Steam + Atmospheric	Pre-steaming does not affect wood properties when subsequently treated above 200°C. Strength remained acceptable even at high temperature	de Cademartori et al. 2013; de Cademartori et al. 2014
E. cloeziana, *E. grandis* (21 year-old)	180, 200 -22 + (180, 200)	Atmospheric	Pre-freezing decreased mass loss and chemical changes, but did not affect brittleness and strength of thermally modified timber	Missio et al. 2015; Missio et al. 2016; de Avila Delucis, Beltrame, et al. 2019; de Avila Delucis, Machado, et al. 2019; Costa et al. 2020
E. saligna (17 year-old)	180, 200, 220, 240 127 + (180, 200, 220, 240)	Atmospheric Steam + Atmospheric	Pre-steaming did not affect wood properties when subsequently treated above 200°C. Strength remained acceptable even at high temperature	de Cademartori et al. 2015
E. saligna (25 year-old)	120, 140, 160, 180	Atmospheric	Increased heat treatment temperature facilitated colour homogenisation	Pincelli et al. 2012
Corymbia citriodora (18 year-old)	160, 180, 200, 220, 240	Nitrogen	Heat treatment reduced extractives from 17.9% in the control to 3.5% at 240°C	Silva et al. 2013
E. grandis, *E. saligna*, *Corymbia citriodora* (18year-old)	180, 220 220, 250, 280	Air Nitrogen	Slope of sorption curves not affected by heat treatment	Almeida et al. 2009
E. bosistoana (50 year-old sapwood)	<150	Surface contact hot plate	Surface charring improved moisture related characteristics but reduced MoE, MoR, compression strength parallel to the grain and hardness	Ibanez et al. 2023; Tuncer et al. 2024

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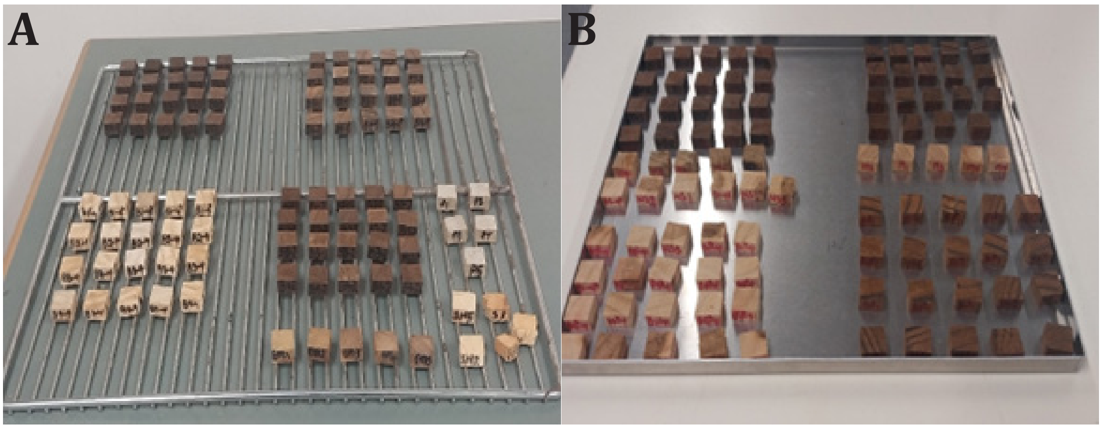

FIGURE S1: Wood blocks after 12 weeks of exposure to *T. versicolor* (A) and *R. placenta* (B)

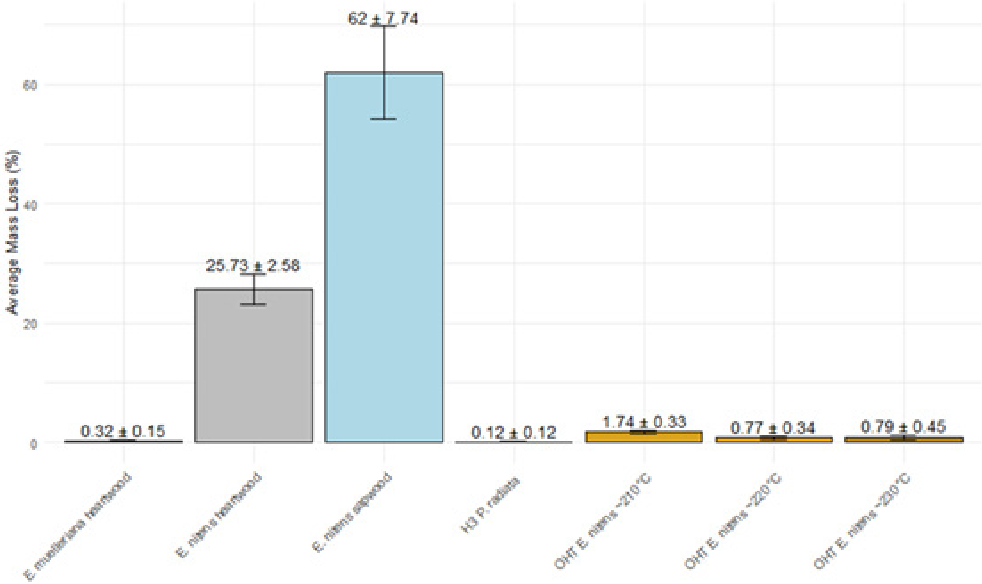

FIGURE S2: Mass loss of oil-heat treated *E. nitens* and control samples after 12-week exposure to the white-rot fungus *Trametes versicolor*

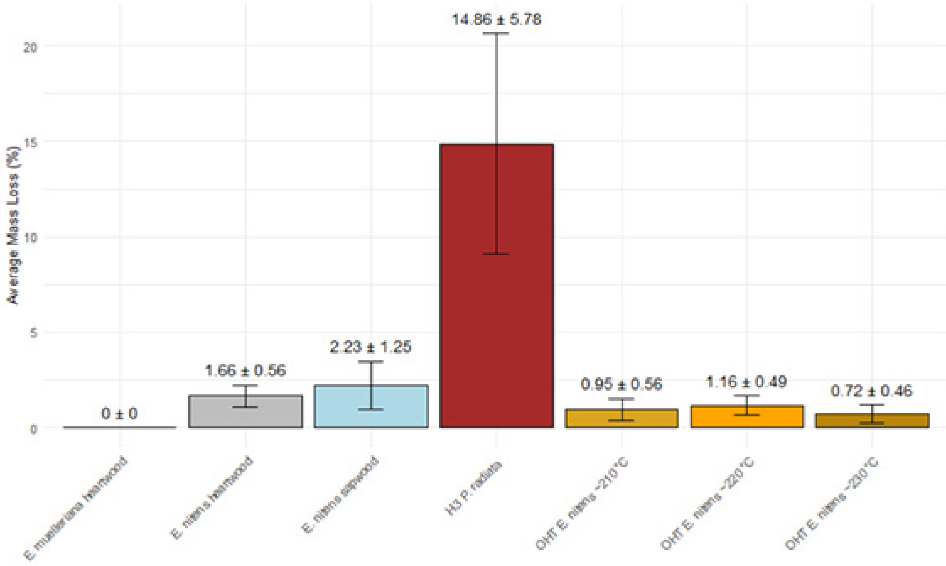

FIGURE S3: Mass loss of oil-heat treated *E. nitens* and control samples after 12-week exposure to the brown-rot fungus *Rhodonia placenta*

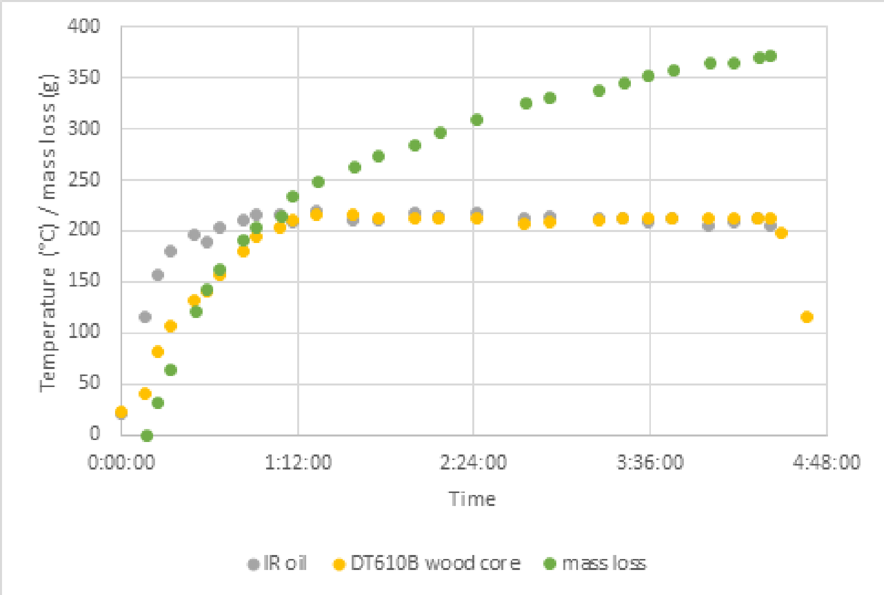

FIGURE S4: Monitored temperature and mass loss during oil heat treatment of set 1. The average oil equilibrium oil temperature over the treatment time of 3 h (from 1:25 h to 4:25 h) was 212°C and the temperature in the core of the sample was 213°C.

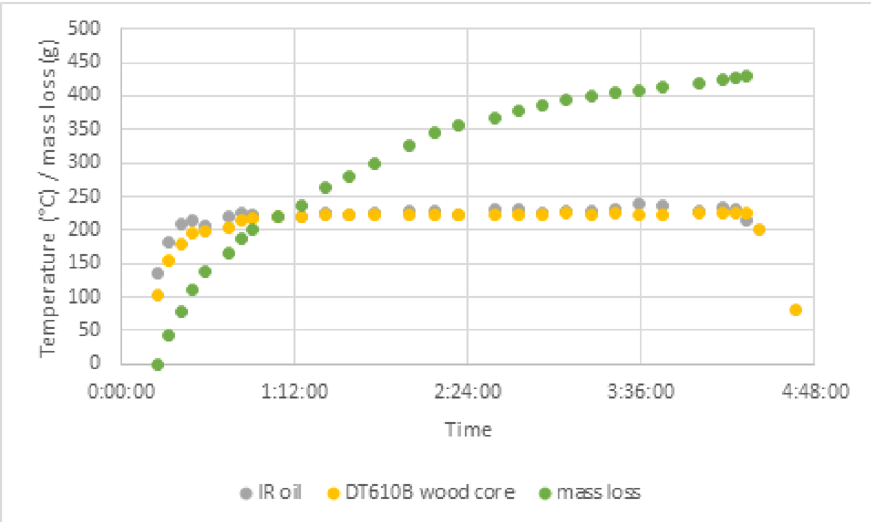

FIGURE S5: Monitored temperature and mass loss during oil heat treatment of set 2. The average oil equilibrium oil temperature over the treatment time of 3 h 30 min (from 0:50 h to 4:20 h) was 228°C and the temperature in the core of the sample was 223°C.

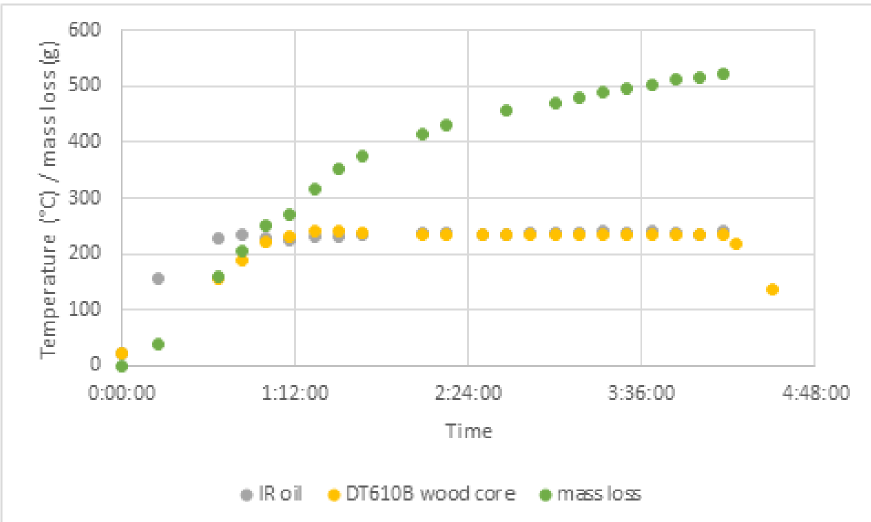

FIGURE S6: Monitored temperature and mass loss during oil heat treatment of set 3. The average oil equilibrium oil temperature over the treatment time of 3 h (from 1:10 h to 4:00 h) was 236°C and the temperature in the core of the sample was 235°C.

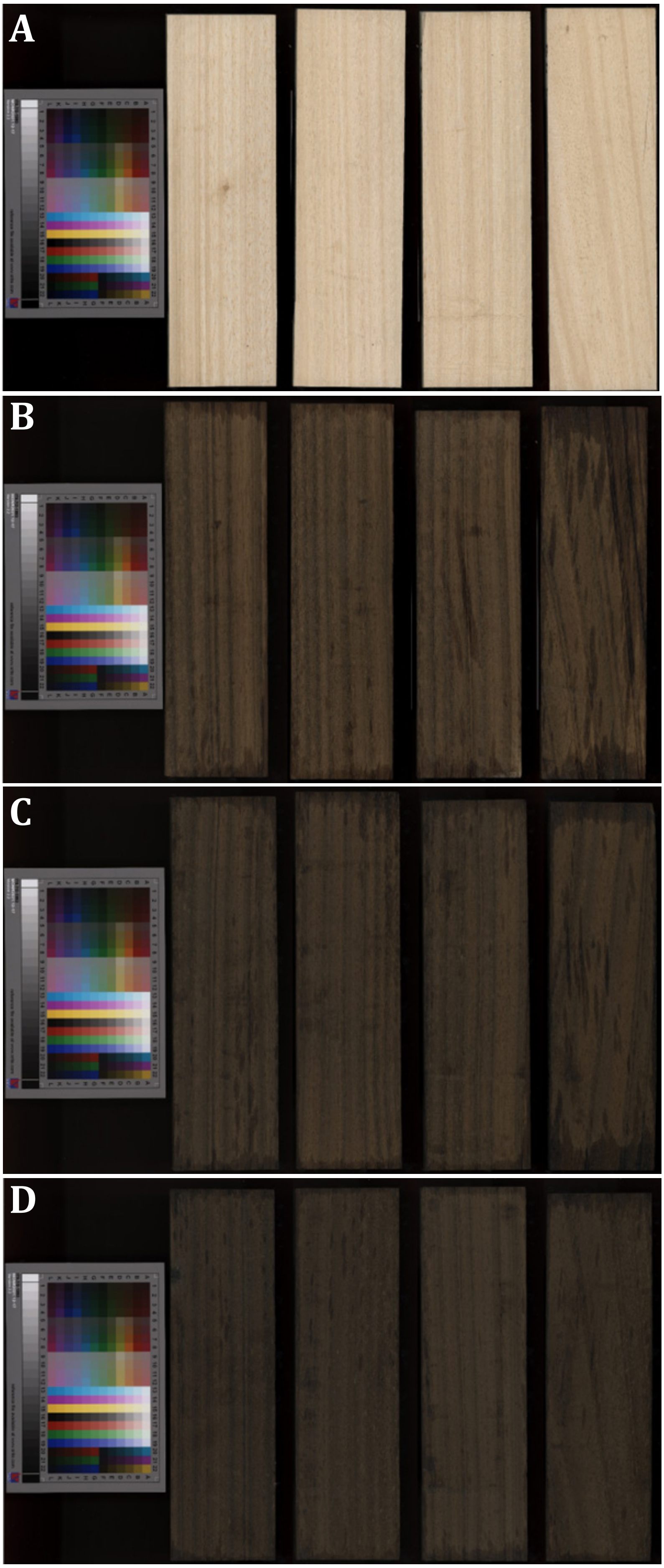

FIGURE S7: From left to right, *E. nitens* boards 1, 2, 3 and 4.
A: control;
B: oil heat treated at ~210°C;
C: oil heat treated at ~220°C;
D: oil heat treated at ~230°C.